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Contents

CHAPTER 1 Introduction to Science

Chapter Outline

1.1 The Nature of Science

Lesson Objectives

- Understand that science is a system based on evidence, testing, and reasoning.
- Describe what the life sciences are and some of the many life science specialties.
- Describe the scientific method and why it is important.
- Define the words "fact," "theory," and "hypothesis."
- Describe some of the tools of life science.
- Know that scientists are required to follow strict guidelines.

Check Your Understanding

- What do you expect to learn from this class?

Introduction

Several interesting questions:

1. Why is modern science producing many more improvements in our lives than it did a hundred years ago? Modern science is based on evidence, inquiry and testing which have replaced personal beliefs, mythology and other biased sources of information.
2. Is there anything that science cannot explain? Yes there is. Questions about ethics (right and wrong) and belief in supernatural forces can not be explained through science.
3. How can we "think like scientists?" To think like a scientist, you would need to:
   (a) ask questions about the world around you and seek new evidence that will help answer questions,
   (b) base your understanding of the world on evidence, testing and reasoning instead of biased belief systems,
   (c) continuously question and test the accuracy of your knowledge and assumptions (including so-called "common sense").

Goals of Science

Science, religion, mythology, and magic share the goal of knowing about and explaining the world, such as the physical world, but their approaches are vastly different. The difference between them is their approach to "knowing." The vastness of the living, physical world includes all organisms (**Figure** 1.1), on land (**Figure** 1.2) and in the sea (**Figure** 1.3). As humans, some of the things we want to know and understand are what makes us healthy, what makes us sick, and how we can protect ourselves from floods, famine and drought.

FIGURE 1.1
bacteria

FIGURE 1.2
A male lion.

FIGURE 1.3
A Humpback whale.

Throughout history, humans have looked for ways to understand and explain the physical world. Try to imagine what humans thought about themselves and the world around them 1,000 years ago, or 5,000 years ago, or more. If you were born then, how would you have explained why the sun moved across the sky, then disappeared? How would you explain why your body changes as you grow, or birth and death? What explanation would you have for lightning, thunder, and storms?

Throughout time, different cultures have created hundreds of different myths and stories and even gods to explain what they saw. Ancient Greeks explained that lightning was a show of their god Zeus' anger. Scandinavians claimed that their god of thunder, Thor, was responsible for the rumbling and bolts of lightning. Without any formal science, many cultures have also blamed diseases, such as epilepsy, on evil spirits and other imaginary entities. For example, there is evidence that many different cultures drilled holes in the skulls of patients who had seizures or other maladies, thinking that they were releasing evil spirits.

Science as a Way of Knowing

During your own and your parents' lifetimes, advances in medicine (**Figure** 1.4), technology, and other fields have progressed faster than any other time in history. This explosion of advances in our lives is largely due to human use of modern science as a way of understanding. Today's scientists are trained to base their comprehension of the world on evidence and reasoning rather than belief and assumptions.

FIGURE 1.4
The anatomy lesson of Dr. Nicolaes Tulp.

Modern science is:

- A way of understanding about the physical world, based on observable evidence, reasoning, and repeated testing.
- A body of knowledge that is based on observable evidence, experimentation, reasoning, and repeated testing.

As we learn more, new information occasionally conflicts with our current understanding. When this happens scientific explanations are revised. The **Figure** 1.5 demonstrates this. However, science cannot scrutinize what is good versus what is bad (morality), because these are values, ideas that lack measurable evidence. Science is not used to examine philosophy or supernatural entities, such as the existence or nonexistence of a god. However, science can be used to examine the effects of these experiences.

FIGURE 1.5
In 1847, a doctor, Ignaz Semmelweis, demonstrated that when he washed his hands before delivering babies fewer women died from infection. Before this, doctors held untested beliefs about the causes of disease, such as a persons behavior, or the air they breathed.

The most important message from this chapter is that **science is not only a way of knowing it is also a way of thinking and reasoning**. Scientists try to look at the world objectively - without bias or making assumptions. How? Scientists learn to be skeptical, to question the accuracy of our ideas. They learn to base their understanding of the physical world on evidence, reasoning and repeated testing of ideas.

To Think Like a Scientist

To think like a scientist, you need to be skeptical about and question your assumptions, including what often seems like common sense. Questioning ideas can often lead to surprising results. For example, if you ask people whether it's easier to keep a plastic cutting board clean or a wooden one clean, most people will think that the plastic board is easier to keep clean and has fewer germs (**Figure** 1.6).

FIGURE 1.6
Which is safer, a plastic or wood cutting board?

Why do most people believe that plastic is safer? Probably because we assume that it is easier to wash germs off plastic than off wood. This assumption is promoted by the makers of plastic cutting boards and it sounds reasonable. After all, wood stains and looks unhygienic; plastic cutting boards come out of the dishwasher shiny and clean looking. But is plastic actually better?

When scientists tested this idea, the answer turned out to be no. The researchers treated used cutting boards with different kinds of germs and then washed the boards. They found, much to their surprise, that gouged and sliced wooden cutting boards had far fewer germs than gouged and sliced plastic boards. The researchers discovered that germs that cause food poisoning, such as *E. coli* and *Salmonella*, are absorbed into the wood and seemed to vanish. On plastic, the germs sit on the surface in cuts in the plastic where they are difficult to clean out but can contaminate food. Furthermore, in a different study of food poisoning, people who used wooden cutting boards were less than half as likely to get sick as people using plastic ones.

"Common sense" may seem to have all the answers, but science is all about following the evidence. So what is good evidence? Evidence is information that can be used to confirm or refute an idea or to explain something. Both scientists and lawyers use evidence to support an idea or to show that an idea is probably wrong. Scientific evidence has certain features, which may be different from legal evidence.

Evidence is:

1. a direct, physical observation of a thing, a group of things, or of a process over time.
2. usually something measurable or "quantifiable."
3. the result of something.

For example, a book falling to the ground is evidence in support of the theory of gravity. A bear skeleton in the woods would be supporting evidence for the presence of bears.

Scientific Theories

Science theories are produced through repeated studies, usually performed and confirmed by many individuals. Scientific theories are well established and tested explanations of observations. These theories produce a body of knowledge about the physical world that is collected and tested through the scientific method (discussed in the Scientific Method lesson).

The word "theory" has a very different meaning in daily life than it does in science. When someone at school says, "I have a theory," they sometimes just mean a hunch or a guess. This everyday meaning for "theory" can confuse people when well-tested and widely accepted scientific theories are discussed by nonscientists. For example, the theory of evolution is a well-established scientific theory that some people incorrectly say is just a hunch.

A **scientific theory** is based on evidence and testing that supports the explanation. Scientific theories are so well studied and tested that it is extremely unlikely that new data will discredit them. The idea that matter is made up of atoms, evolution, and gravity are all scientific theories about how the world works that scientists accept as fundamental principles of basic science. However, any theory may be altered or revised to make it consistent with new evidence.

Two Important Science Theories

In the many life sciences, there are possibly hundreds or thousands of theories. Yet there are at least two fundamental theories, which provide a foundation for modern biology. They are:

1. The Cell Theory
2. The Theory of Evolution

The Cell Theory

The Cell Theory states that:

- All organisms are composed of cells (**Figure** 1.7).
- Cells are the basic units of structure and function in an organism.
- Cells only come from preexisting cells; life comes from life.

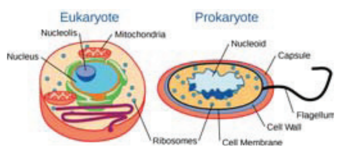

FIGURE 1.7
The two types of cells, eukaryotic (left) and prokaryotic (right).

The development of the microscope in the mid 1600s made it possible to come up with this theory (**Figure** 1.8).

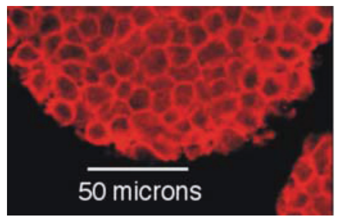

FIGURE 1.8
A mouse cell viewed through a microscope.

The Theory of Evolution

In biology, evolution is the process of change in the inherited traits of a population of organisms over time. Natural selection is the process where organisms that are better suited to the environment are more likely to survive and reproduce than others that are less suited to the environment. This theory basically states that better suited organisms live longer and have an easier time reproducing, passing on their traits that made them better suited to their environment. The theory of evolution by natural selection is often called the "great unifier" of biology, because it applies to every field of biology. It also explains the tremendous diversity and distribution of organisms across Earth. All living organisms (**Figure** 1.9 is a sampling) on Earth are descended from common ancestors.

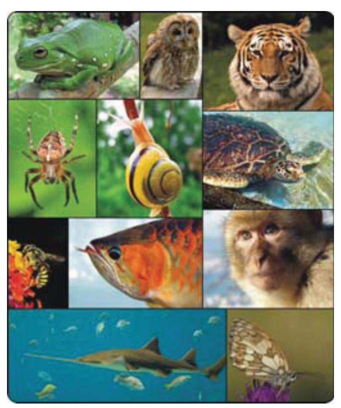

FIGURE 1.9
Evolution explains the millions of varieties of organisms on Earth.

Lesson Summary

- Science is a way of understanding (knowing) about the physical world that is based on evidence, reasoning, and testing predictions.
- A body of knowledge that has been thoroughly tested can still undergo further testing, and revisions as new evidence and questioning are raised.
- Science differs from other ways of knowing, because it is entirely based on observable evidence and its explanations are constantly questioned and tested.
- Science produces theories and general knowledge that allow us to better understand the world and to apply this knowledge to solve problems.

Review Questions

1. How is modern science different from other ways of knowing?
2. Explain why science cannot be used to examine whether someone is good or bad?
3. How is the scientific meaning of the word "theory" different from its use in day-to-day conversation?
4. What is the goal of science?
5. What is modern science?
6. What qualities do you need to THINK like a scientist?

Points to Consider

- Next we are going to discuss the scientific method. You may have heard someone say that you can ruin your eyes if you sit too close to the television set.
- Describe how "thinking like a scientist" could help you figure out if this common sense idea is true or false.

1.2 The Scientific Method

Lesson Objectives

- Consider how the scientific method is one of the most important reasons for how modern science is advancing more rapidly than in the past.
- Describe the scientific method as a process.
- Explain why the scientific method allows scientists and others to examine the physical world more objectively than other ways of knowing.
- Describe the steps involved in the scientific method.

Check Your Understanding

- What is science?
- What is a scientific theory?

Introduction

The **scientific method** is an inquiry process used to investigate the physical world using observable evidence and testing. This method allows scientists to "conduct" science in a uniform process. This process allows the information collected to be reproduced by other scientists, and most importantly, this process allows the information to be accepted and trusted.

Observations, Data, Hypotheses, and Experiments

Imagine that you are scientist who wants to know something like, "Why do whales migrate?" or "Why do some people get more colds than others do?" Two hundred years ago you could have come up with theories without necessarily thoroughly testing your ideas. But there were many exceptional scientists who made outstanding contributions. Here is a painting of Michael Faraday in his laboratory in the Royal Institution in England during the 1800s (**Figure** 1.10). Michael Faraday is best known for his contributions to chemistry, and he probably used some form of the scientific method to answer his questions.

FIGURE 1.10
Michael Faraday in his laboratory at the Royal Institution during the mid 1800s.

As a modern scientist today, you would use the scientific method, collecting evidence to test your hypothesis and answer your questions. The scientific method presents a general idea of how science is conducted; **it is not a strict pattern for doing research**. Scientists use many different variations of the scientific method to meet their specific needs. Almost all versions of the scientific method include the following steps, though not always in the same order:

1. Make observations
2. Identify a question you would like to answer about the observation
3. Research: find out what is already known about your observation
4. Form a hypothesis
5. Test the hypothesis
6. Analyze your results
7. Repeat or communicate results

A **hypothesis** is a proposed explanation that allows you to make predictions about what ought to happen if the hypothesis is true. If the predictions are accurate, that provides support for the hypothesis. If the predictions are incorrect, that suggests the hypothesis is wrong.

Make Observations

Observe something in which you are interested. Here is an example of a real observation made by students in Minnesota (**Figure** 1.11). Imagine that you are one of the students who discovered this strange frog.

FIGURE 1.11
A frog with an extra leg.

Imagine that you are on a field trip to look at pond life. While collecting water samples, you notice a frog with five legs instead of four. As you start to look around, you discover that many of the frogs have extra limbs, extra eyes or no eyes. One frog even has limbs coming out of its mouth. You look at the water and the plants around the pond to see if there is anything else that is obviously unusual like a source of pollution. Observations are what you can detect with your five (5) senses; sight, sound, touch, smell, taste. An **Inference** is an assumption based on past knowledge. Observations should not contain inferences.

Identify a Question That is Based on Your Observations

The next step is to ask a question about these frogs. For example, you may ask why so many frogs are deformed. You may wonder if there is something in their environment causing these defects. You could ask if deformities are caused by such materials as water pollution, pesticides, or something in the soil nearby (**Figure** 1.12).

Yet, you do not even know if this large number of deformities is "normal" for frogs. What if many of the frogs found in ponds and lakes all over the world have similar deformities? Before you look for causes, you need to find out if the number and kind of deformities is unusual. So besides finding out *why* the frogs are deformed, you should also ask:

"Is the percentage of deformed frogs in pond A (your pond) greater than the percentage of deformed frogs in other places?"

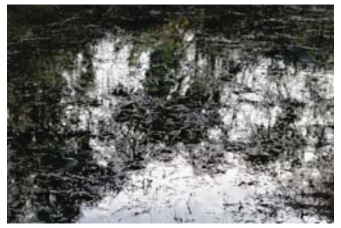

FIGURE 1.12
A pond with frogs.

Research Existing Knowledge About the Topic

No matter what you observe, you need to find out what is already known about your topic. For example, is anyone else doing research on deformed frogs? If yes, what did they find out? Do you think that you should repeat their research to see if it can be duplicated? During your research, you might learn something that convinces you to alter your question.

Construct a Hypothesis

A hypothesis is a proposed explanation of an observation. For example, you might hypothesize that a certain pesticide is causing extra legs. If that's true, then you can *predict* that the water in a pond of healthy non deformed frogs will have lower levels of that pesticide. That's a prediction you can test by measuring pesticide levels in two sets of ponds, those with deformed frogs and those with nothing but healthy frogs. A hypothesis is an explanation that allows you to predict what results you will get in an experiment or survey.

The next step is to state the hypothesis formally. A hypothesis must be "testable."

Example:

After reading about what other scientists have learned about frog deformities, you predict what you will find in your research. You construct a hypothesis that will help you answer your first question.

Any hypothesis needs to be written in a way that it can:

1. Be tested using evidence.
2. Be falsified (found false/wrong).
3. Provide measurable results.
4. Provide yes or no answers.

For example, the following hypothesis can be tested and provides yes or no answers:

"The percentage of deformed frogs in five ponds that are heavily polluted with a specific chemical X is higher than the percentage of deformed frogs in five ponds without chemical X."

Test Your Hypothesis

The next step is to count the healthy and deformed frogs and measure the amount of chemical X in all the ponds. This study will test the hypothesis. The hypothesis will be either true or false. Testing a hypothesis is usually done through an experiment. Parts of the experiment need to be identified such as the variables and control.

Variables are the part of the experiment that are changing. There are two types of variables; Independant Variable and dependant variable. The **independant variable** is the part that is being changed by the experimentor. In the case of the deformed frogs it would be the water pollution, pesticides, or soil by the water (chemical X) that is being

measured. A **dependant variable** is what has changed based on the independant variable. For example the number of frogs with deformities.

A **control** is an experiment that all other experiments are being compared too. For example you may use a pond in another town as the control to see if frogs are just born with extra legs.

An example of a hypothesis that is not testable would be: "The frogs are deformed because someone cast a magic spell on them." You cannot make any predictions based on the deformity being caused by magic, so there is no way to test a magic hypothesis or to measure any results of magic. There is no way to prove that it is not magic, so that hypothesis is untestable and therefore not interesting to a scientist.

Analyze Data and Draw a Conclusion

If a hypothesis and experiment are well designed, the experiment will produce measurable results that you can collect and analyze, and then develop a conclusion. Measurable results such as the number of frogs that are mutated, is called **Quantitative Data**. If there is no way to measure the results the data such as the frogs in the pond are health, the data is called **Qualitative Data**. The conclusion should tell you if the hypothesis is true or false and contain an explaination of why.

Example:

Your results show that pesticide levels in the two sets of ponds are statistically different, but the number of deformed frogs is almost the same when you average all the ponds together. Your results demonstrate that your hypothesis is either false or the situation is more complicated than you thought. This gives you new information that will help you decide what to do next. Even if the results supported your hypothesis, you would probably ask a new question to try to better understand what is happening to the frogs and why. When you are satisfied that you have accurate information, you share your results with others.

You will probably revise your hypothesis and design additional experiments along the way.

Communicate Results

Scientists communicate their findings in a variety of ways. For example, they may discuss their results with colleagues, talk to small groups of scientists, give talks at large scientific meetings, and write articles for scientific journals. Their findings may also be communicated to journalists. Scientific articles include the questions, methods and the conclusions from their research. Other scientists may try to repeat the experiments or change them. Scientists spend much time sharing and discussing their ideas with each other. Different scientists have different kinds of expertise they can use to help each other. When many scientists have independently come to the same conclusions, a scientific theory is developed. A scientific theory is a well-established explanation of an observation. It is generally accepted among the scientific community.

Example:

You eventually decide that you have strong results to share about frog deformities. You write an article and give talks about your research. Your results could contribute towards solutions.

Basic and Applied Science

Science can be "basic" or "applied." The goal of basic science is to understand how things work - whether it's why things fall on the floor or the structure of cells. Basic science is the source of most scientific theory and new knowledge. Applied science is using scientific discoveries to solve practical problems or to create new technologies.

Even though basic research is not intended to solve problems directly, basic research always provides the knowledge that applied scientists need to solve problems. For example, medicine and all that is known about how to treat

patients is applied science based on basic research (**Figure** 1.13).

FIGURE 1.13
A healthy newborn being examined by a doctor.

Lesson Summary

- The scientific method is an inquiry process used to investigate the physical world using observable evidence and testing.
- A hypothesis is a proposed explanation of an observation; it is used to test an idea.
- A theory is a well-established explanation of an observation.
- A hypothesis must be written in a way that can be tested, is falsifiable (to be able to prove that something is false), is measurable, and will help answer the original question.

Review Questions

1. How is a hypothesis different from a theory?
2. What does a hypothesis need to include?
3. What does "falsifiable" mean?
4. List the steps of the Scientific Method?
5. What is used in making observation?
6. What parts should each experiment contain?
7. What is the purpose of an experiment or test of your hypothesis?
8. What is basic research?
9. What is applied research?
10. What does a scientist do if their research results conflict with previous theories or popular knowledge?
11. Is it OK for scientists to change their ideas?

Points to Consider

- How do you think scientific "tools" can help a scientist?
- What do you think is one of the more common tools of the life scientist?

1.3 Tools of Science

Lesson Objectives

- Describe the growing number of tools available to investigate different features of the physical world.
- Describe how microscopes have allowed humans to view increasingly small tissues and organisms that were never visible before.

Check Your Understanding

- What is the scientific method?
- What is an experiment?

Using Microscopes

Microscopes, tools that you may get to use in your class, are some of the most important tools in biology. **Figure** 1.14 Before microscopes were invented in 1595, the smallest things you could see on yourself were the tiny lines in your skin. The magnifying glass, a simple glass lens, was developed about 1200 years ago. A typical magnifying glass may have doubled the size of an image. But microscopes allowed people to see objects as small as individual cells and even large bacteria. Microscopes let people see that all organisms are made of cells. Without microscopes, some of the most important discoveries in science would have been impossible.

FIGURE 1.14
Basic light microscopes opened up a new world to curious people. 1, ocular lens or eyepiece; 2, nose piece; 3, objective lenses; 4, coarse adjustment knob; 5, fine adjustment knob; 6, object holder or stage; 7, light (illuminator); 8, diaphragm and condenser 9, stage clips.

Microscopes are used to look at things that are too small to be seen by the unaided eye. **Microscopy** is a technology for studying small objects using microscopes. A microscope that magnifies something two to ten times (indicated by 2X or 10X on the side of the lens) may be enough to dissect a plant or look closely at an insect. Using even more powerful microscopes, scientists can magnify objects to two million times their real size.

Some of the very best early optical microscopes were made four hundred years ago by Antoine van Leeuwenhoek (**Figure** 1.15), a man who taught himself to make his own microscopes. When he looked at a sample of scum from his own teeth, Leeuwenhoek discovered bacteria. In rainwater, he saw tiny protozoa. Imagine his excitement when

he looked through the microscope and saw this lively microscopic world. Leeuwenhoek discovered the first one-celled organisms (protists), the first bacteria, and the first sperm. Robert Hooke, an English natural scientist of the same period of history, used a microscope to see and name the first "cells" (**Figure** 1.16), which he discovered in plants.

FIGURE 1.15
Antoine van Leeuwenhoek, a Dutch cloth merchant with a passion for microscopy. Bacteria were discovered in 1683 when Antoine Van Leeuwenhoek used a microscope he built to look at the plaque on his own teeth.

FIGURE 1.16
Robert Hookes early microscope.

Some modern microscopes use light, as Hooke's and van Leeuwenhoek's did, but others may use electron beams or sound waves.

Researchers now use four kinds of microscopes:

1. **Light microscopes** allow biologists to see small details of biological specimens. Most of the microscopes used in schools and laboratories are light microscopes. Light microscopes use refractive lenses, typically made of glass or plastic, to focus light either into the eye, a camera, or some other light detector. The most powerful light microscopes can magnify images up to 2,000 times. Light microscopes are not as powerful as other higher tech microscopes but they are much cheaper and anyone can own one and see many amazing things.
2. **Transmission electron microscopes** (TEM) focus a beam of electrons through an object and can magnify an image up to two million times with a very clear image ("high resolution").
3. **Scanning electron microscopes** (SEM) (**Figure** 1.16) allow scientists to map the surfaces of extremely small objects. These microscopes slide a beam of electrons across the surface of specimen, producing detailed maps of the shapes of objects.
4. **Scanning acoustic microscopes** use sound waves to scan a specimen. These microscopes are useful in biology and medical research.

FIGURE 1.17
A scanning electron microscope.

Using Maps and Other Models

You use models for many purposes. A volcano model, is not the same as a volcano, but it is useful for thinking about real volcanoes. We use street maps to represent where streets are in relation to each other. A model of planets may show the relationship between the positions of planets in space. Biologists use many different kinds of models to simulate real events and processes. Models are often useful to explain observations and to make scientific predictions.

Some models are used to show the relationship between different variables. For example, the model in **Figure** 1.17 says that when there are few coyotes, there are lots of rabbits (left side of the graph) and when there are only a few rabbits, there are lots of coyotes (right side of the graph). You could make a prediction, based on this model, that removing all the coyotes from this system would result in an increase in rabbits. That's a prediction that can be tested.

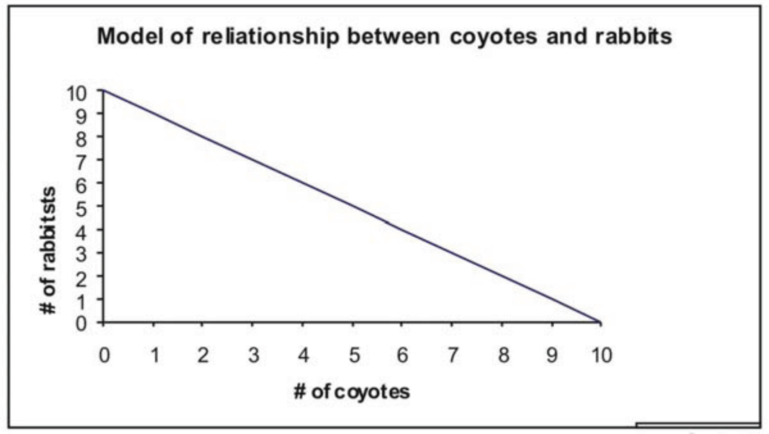

FIGURE 1.18
This graph shows a model of a relationship between a population of coyotes (the predators) and a population of rabbit, which the coyotes are known to eat (the prey).

Graphs and Tables

You have heard the phrase, "A picture is worth a thousands words." Graphs and tables are commonly used in science to summarize data collected. It is important to be able to look at a graph and understand what information you can gather from it. What observation can you make about the population in the "Town populations graph?"

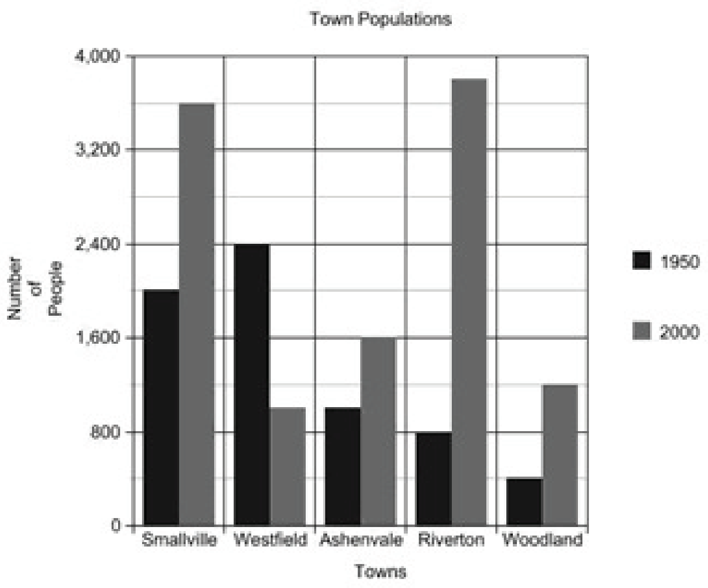

FIGURE 1.19
Town populations graph

Not all graphs look the same. The "Coyote and rabbit" graph is a linear graph and the "town population" graph is a bar graph. The "Insect" graph is a pie graph. Each type of graph has advantages in telling different types of data.

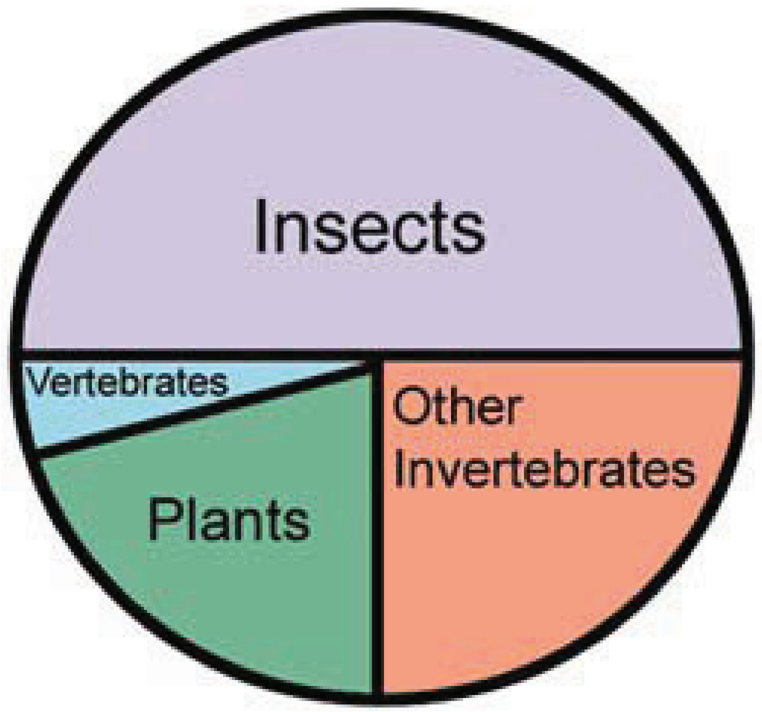

FIGURE 1.20
Insect Graph

Lesson Summary

- From the time that the first microscope was built, over four hundred years ago, microscopes have been used to make major discoveries.
- Life science is a vast field; different kinds of research usually require very different tools.
- Scientists use maps and models to understand how features of real events or processes work.

Review Questions

1. What did van Leeuwenhoek discover when he looked at plaque from his own teeth under the microscope?
2. What does the symbol 10X on the side of a microscope mean?
3. What is a scientific model?
4. Look at the predator/prey (coyote/rabbit) model again. What does the model predict would happen to the rabbit population if you took away all the coyotes?
5. How long ago were the first microscopes invented?
6. According to the "town populations" graph, Which town grew the fastest?
7. According to the "Insect" graph which group of organisms has the most number of species?

Points to Consider

- What could be risks of doing field research?
- So what do you think biologists do to protect themselves?

1.4 Measuring in Science

Lesson Objectives

- Understand the history of Measuring in Science
- Recognized the Prefixes of the Metric system
- Be able to convert from one prefix to another prefix when given a set of numbers.

Check your understanding

- Where is the metric system used in the world?
- What is another name for the metric system?

Metric system

The **metric system** is an international systems of measurement, first adopted by France in 1791, that is the common system of unit of measurement used by most of the world. Since the 1960s the International System of Units ("*Système International d'Unités*" in French language, hence "SI") has been the internationally recognised International standard metric system. Metric units are universally used in scientific work, and widely used around the world for personal and commercial purposes. A standard set of prefixes in powers of **ten** may be used to derive larger and smaller units from the base units.

One goal of the metric system is to have a single unit for every thing measured. Another goal is to avoid the need to convert from one unit to another. All lengths and distances, for example, are measured in metres, or thousandths of a metre (millimetres), or thousands of metres (kilometres), all liquids are measured in liters and mass (weight) is measured in grams. There is no different unit with different conversion factors, such as inches, Foot (length), yards, fathoms, rod (unit)s, chain (unit)s, furlongs, miles, nautical miles, league (unit)s, etc. Multiples and submultiples are factors of powers of ten, so that one can convert by simply moving the decimal place: 1.234 metres is 1234 millimetres, 0.001234 kilometres, etc.

The names of multiples and submultiples are formed with **SI prefix**. They include **kilo**- (thousand, 10^3), **centi**- (hundredth, 10^{-2}) and **milli**- (thousandth, 10^{-3}). For example, long distances are normally stated in thousands of kilometres, not megametres.

Decimal multiples

The metric system is decimal, in the sense that all multiples and submultiples of the base units are factors of powers of ten of the unit. Fractions of a unit are not used. This is for simplicity. Using the metric system prevents having to convert unit such as 12 inches per foot, 3 feet per yard. At most, differences in expressing results are simply a matter of shifting the decimal point or changing an exponent; for example, the speed of light may be expressed as 299,792.458 km/s or 2.99792458×10^8 m/s. The practical benefits of a decimal system are such that it has been used to replace other non-decimal systems outside the metric system of measurements; for example currencies.

Prefixes

All derived units would use a common set of prefixes for each multiple. The prefix *kilo* could be used for mass (*kilogram*) or length (*kilometre*) both indicating a thousand times the base unit. The function of the prefix is to multiply or divide the measure by a factor of ten, one hundred or a positive integer power of one thousand.

TABLE 1.1: **metre**

Unit	Relation to base
kilometre	10^3 metres
hectometre	10^2 metres
decametre	10^1 metres
metre	
decimetre	10^{-1} metres
centimetre	10^{-2} metres
millimetre	10^{-3} metres

TABLE 1.2: **litre**

Unit	Relation to base
kilolitre	10^3 litres
hectolitre	10^2 litres
decalitre	10^1 litres
litre	
decilitre	10^{-1} litres
centilitre	10^{-2} litres
millilitre	10^{-3} litres

Lesson Summary

- The metric system is a system that measures in units of tens
- the prefixes greater than one are greek and the prefixes less than one are latin
- Most of the world uses the Metric system which is also know as the "international system of units" or "SI."

Review Questions

1. Where was the metric system first adopted?
2. What are the two (2) goals of the metric system?
3. Is the prefix kilo mean that the measurement will be larger than 1 or smaller than 1?
4. If I was measuring how much Pepsi I drank today, what unit of measure would I use? (hint: onces is incorrect)
5. If the maximum amount of Tylenol I could take in one day was 4 grams, How many milligrams could I take?

Student Vocabulary: words you will need to define on your own.

Theory

Hypothesis

Variable

Measure

Evidence

Data

Inference/Infer

Compare

Predict

Interpret

Analyze

Observation

Classify

Experiment

Assumption

Skeptical

Generalize

Conclude

Relate

Calculate

Describe

Technology

Investigation

Tentative

Ethical

Replicability

1.5 References

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Chapter 2 Ecological Levels of Organization and the Flow of Energy through those Levels

Chapter Outline

2.1 Introduction to Ecology

Lesson Objectives

- Define ecology
- Explain what organisms and environments are.
- Describe how abiotic and biotic factors influence ecology.
- Define the levels of organization in ecology.

Check Your Understanding

- What is adaptation?
- What are biotic and abiotic factors?
- How can scientists study ecology at different levels?

Introduction

Organisms can be studied at many different levels, from biochemical and molecular, to cells, tissues and organs, to individuals, and finally at the ecological level: populations, communities, ecosystems and to the biosphere as a whole. Because of its focus on the higher levels of the organization of life on earth, ecology draws heavily on many other branches of science. Can you think of what some of these might be?

What is Ecology?

Ecology is the scientific study of how living organisms interact with each other and with their environment. Because of its broad scope, ecology draws from other branches of science, including geology, soil science, geography, meteorology, genetics, chemistry, and physics.

The study of ecology can also be broken down into sub-disciplines. Thus, if you were focusing on, for example, how the physiology of an organism influences the way that organism interacts with the environment, you would be studying the sub-discipline of ecophysiology. Similarly, you could come up with terminology for studying the roles of behavior, populations, communities, ecosystems, landscapes, evolution, and even politics!

You could also sub-divide ecology according to the species of interest into fields such as animal ecology, plant ecology, insect ecology, etc., or according to **biome**, an ecological formation that exists over a large region, such as the Arctic, the tropics, or the desert (see **figure below**). Perhaps you can come up with some of your own terms for combining some of these specialties, or think of some other specialties yourself!

Finally, because of the way ecologists study their discipline and because of the number of other fields involved, many methods can be employed to study how organisms interact with each other and their environment. Can you think of what some of these methods might be?

One obvious type of research that comes to mind is field studies, since ecologists generally are interested in the world of nature. This involves collecting data in the natural world, as opposed to laboratory settings with controls. One example of this kind of study is determining how many organisms occupy a specific geographical area. This usually involves a technique called sampling, where an area is divided into a certain sized plot, and the number of organisms in that area is counted.

Ecological principles can be studied in the laboratory as well. Perhaps you can think of some ways in which some aspects of ecology can be isolated in the lab. Statistical analysis is also used for analyzing both field and laboratory data. Finally, ecologists often use computer simulations to model complex ecological systems and to help predict how future environmental changes can affect a system. Can you think of some possible environmental change in the future that could be studied?

Organisms and Environments

All organisms have the ability to grow and reproduce, properties which require materials and energy from the environment. An organism's environment includes physical nonliving properties (**abiotic** factors), such as sunlight, climate, soil, water and air, and biological properties (**biotic** factors), which comporise the other living organisms, of the same or different species, that share its habitat. Biotic and abiotic factors will be further discussed in the Ecosystems lesson.

An example of how biotic factors influence the environment in which an organism lives can be seen in the primitive atmosphere. The first photosynthesizing organisms on Earth produced oxygen. This led to an oxygen-rich atmosphere, which caused life forms for which oxygen was toxic to die, and other organisms which depend upon oxygen to evolve.

Levels of Organization in Ecology

Ecology can be studied at a wide range of levels, from the smallest unit, at the individual level, to the largest, or most inclusive, the **biosphere** (the portion of the planet occupied by living matter (See **Figure Below**) (**Table** 2.12.1). Between the individual level and the biosphere, from smallest to largest, is the **population** (organisms belonging to the same species that occupy the same area and interact with one another) level, the **community** (populations of different species that occupy the same area and interact with one another) level, and the **ecosystem** (a natural unit composed of all the living forms in an area, functioning together with all the abiotic components of the environment (see figure below)) level.

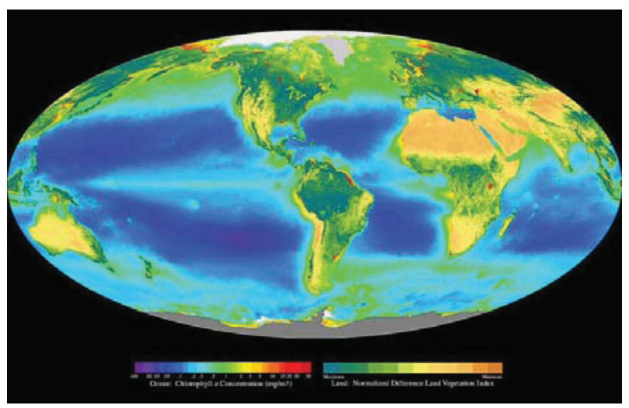


TABLE 2.1: Ecological Range

Level	Definition
Organism	one single life fom of a species.
population	two or more organisms belonging to the same species that occupy the same area and interact with one another
community	two or more populations of different species that occupy the same area and interact with one another
ecosystem	a natural unit composed of communities, functioning together with all the abiotic components of the environment
biosphere	All ecosystems (biomes) of the planet occupied by living matter

Ecologists study ecosystems at every level. They can ask different types of questions at each level. Examples of these questions are given in **Table** 2.22.2, using the Zebra as an example.

TABLE 2.2: Ecological Ecosystems

Level	Question
Individual	How do zebras regulate internal water balance?
Population	What factors control zebra populations?
Community	How does a disturbance influence the number of mammal species in African grasslands?
Ecosystem	How does fire affect nutrient availability in grassland ecosystems?
Biosphere	What role does concentration of atmospheric carbon dioxide play in the regulation of global temperature?

Lesson Summary

- Ecology is the scientific study of how living organisms interact with each other and with their environment.
- The study of ecology can be broken down into subdisciplines and can be studied using various methods.

- The organism's environment includes abiotic and biotic factors.
- Levels of organization in ecology include the organism, population, community, ecosystem and biosphere.

Review Questions

1. What are three ways of sub-dividing the study of ecology? Give an example of each.
2. Name four types of research studies or methods that ecologists use.
3. Laboratory studies are valuable for studying ecological principles in that certain factors can be isolated and manipulated in a laboratory setting. Give an example of how the effect of an abiotic factor could be evaluated in the laboratory and the response of an organism measured.
4. A question that an ecologist could ask at the population level is "What factors control Zebra populations?" Think of two examples in which another species might influence the Zebra population.

Points to Consider

- How do you think the study of ecology would be applied at the level of the population and what study methods do you think might be used?
- What do you think causes populations to grow?

2.2 Populations

Lesson Objectives

- Explain what a population is.
- Describe how births, deaths and migration affect population size.
- Explain population dynamics.
- Describe how limiting factors affect population growth.
- Describe growth of the human population.

Check Your Understanding

- What is ecology?
- How does an organism interact with its environment?

Introduction

The study of populations is important to better understand the health and stability of a population. Population growth is dynamic (ever changing). Such factors as births, deaths and migration influence population size. Different models explain how populations grow. Limiting factors can help determine how fast a population grows. All of these aspects of population biology can be applied to the study of human population growth.

What is a Population?

A **population** is comprised of two or more organisms belonging to the same species, all living in the same area and interacting with each other. Since they live together in one area, members of the same species form an interbreeding unit. Ecologists who study populations determine how healthy or stable they are and how they interact with the environment, by asking specific questions, such as: Is the population stable, growing, or declining, and what factors affect the stability, growth, or decline the population?

In determining the health of a population, one must first measure its size or the **population density**, the number of individuals per unit area or volume. Population size or density can also be examined with respect to how individuals are distributed. How individuals are spaced within a population is referred to as **dispersion**. Some species may show a clumped or clustered distribution (**Figure** 2.21) within an area, others may show a uniform, or evenly spaced (**Figure** 2.22), distribution and still others may show a random, or unpredictable, distribution.

Figure 2.21

Figure 2.22

Other factors of importance in the study of populations are age and sex. The proportion of males and females at each age level gives information about **birth rate** (number of births per individual within the population per unit time) and **death rate** (number of deaths within the population per unit time), and this age structure may give further information about a population's health. For example, an age structure with most individuals below reproductive age often indicates a growing population. A stable population would have roughly equal proportions of the population at each age level, and a population with more individuals at or above reproductive age describes a declining population.

Another pattern in populations has to do with how they change with time. Survivorship curves – graphing the population numbers over time - allow us to study how populations grow and change, a topic that will be considered in greater detail in subsequent lessons.

Births, Deaths, and Migration

Births, deaths and migration all affect population density and growth. The population growth rate is the rate at which the number of individuals in a population increases. Population growth rate depends on birth rate and on death rate. The growth rate then is represented by the equation:

growth rate = birth rate – death rate.

According to this equation, if the birth rate is greater than the death rate, then the population grows; if the death rate is greater, then the population declines. If the birth and death rates are equal, then the population remains stable.

Factors which influence a successful reproduction are age at first reproduction, frequency of reproduction, the number of offspring, parental care, reproductive lifespan, and death rate of offspring. In birds, **altricial** (helpless at birth and requiring much parental care (**Figure** 2.23) and **precocial** (independent at birth or hatching and requiring little parental care (**Figure** 2.24) strategies use different reproductive systems to ensure breeding success.

Figure 2.23

Figure 2.24

Migrations and other movements in and out of populations affect population density as well. Therefore, both birth and **immigration** (movement of individuals into a population from other areas) rates increase the population growth rate, while death and **emigration** (movement of individuals out of a population) rates decrease the population rate. The earlier growth rate equation now looks like this:

growth rate = (birth rate + immigration rate) – (death rate + emigration rate)

One type of migration that you are probably pretty familiar with is the direct, often seasonal, movement of a species that results in a predictable change for that population size. Maybe you've heard that 'birds fly south for the winter.' Examples of this migration are the thousands-of-miles migrations that many birds perform in the fall and then again in the spring when they return to their original habitat (**Figure** 2.25). Another example of a long-distance migration is the movements of Monarch butterflies from their Mexican wintering grounds to the northern summer habitats (in various regions of the United States) and back again. These types of migrations move entire populations from one set of location and environmental conditions to another.

Figure 2.25

Population Growth

Under ideal conditions, given unlimited amounts of food, moisture, and oxygen, and suitable temperature and other environmental factors, oxygen-consuming organisms show exponential or geometric growth - as the population grows larger, the growth rate increases. This is shown as the "J-shaped curve" in **Figure** 2.1. You can see that the population grows slowly at first, but as time passes, growth occurs more and more rapidly.

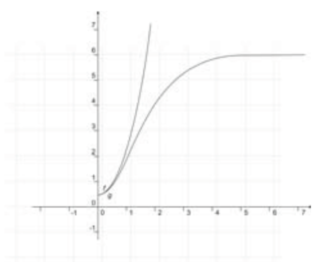


FIGURE 2.1
Line 1 shows exponential growth, Line 2 shows logistic growth which how populations usually look as they grow.

These ideal conditions are not often found in nature. They occur sometimes when populations move into new or unfilled areas. If ideal conditions were found all the time, what would you expect to happen to populations?

In nature, limits occur. One basic requirement for life is energy; growth, survival and reproduction all require this. Do you think energy supplies are limited or unlimited?

The answer is they are limited and therefore organisms must use these resources and others wisely. How do you think this affects the way organisms grow and what do you think the growth rate would look like?

In nature, under more realistic conditions, at first populations grow exponentially (J-shaped curve), but as populations increase, rates of growth slow and eventually level off. This is shown as an "S-shaped curve" in **Figure** 2.1. Why do you think occurs? It's because various factors limit the growth of populations. Can you think of some of those factors?

Limiting Factors

Limiting factors that can lower the population growth rate include reduced food supply, water resources and reduced space and shelter. These can have the effect of lowering birth rates, increasing death rates, or can lead to emigration. This growth model is known as the logistic (S-curve) model, and looks different than the one for exponential growth (**Figure** 2.1). In this case, the growth rate begins as proportional to the size of the population, but at higher population levels, competition for limited resources leads to lower growth rates. Eventually, the growth rate stops increasing and the population becomes stable.

This plateau in growth is known as the **carrying capacity**, or the maximum population size that can be supported in a particular area without degradation of the habitat. Limiting factors determine what the carrying capacity is.

In general, a limiting factor is a living or nonliving property of a population's environment, which regulates population growth. There are two different types of limiting factors: **density-dependent factors** and **density-independent factors.**

Density-dependent factors, such as food supply, promote competition between members of the same population for the same resource, as the population increases in size and there is more crowding. Therefore, the population size is limited by such factors.

In the example of food supply, when population size is small, there is plenty of food for each individual and birth rates are high. As the population increases, the food supply decreases and birth rates decline, causing the population growth rate to decrease. Food shortages can eventually lead to an increase in death rates or emigration, therefore leading to a negative growth rate and lower population size. With a lower population size, each individual has more food and the population begins to increase again, reaching the carrying capacity. Can you think of some other density-dependent limiting factors?

Such factors could include light, water, nutrients or minerals, oxygen, the ability of an ecosystem to recycle nutrients and/or waste, disease and/or parasites, temperature, space, and predation. Can you think of some other factors that limit populations, but seldom regulate them? That means that these factors act irregularly, regardless of how dense the population is. Populations limited by such factors seldom reach carrying capacity.

An example of this other kind of factor, a density-independent factor, is weather. For example, an individual Agave americana (century plant) has a lifespan dependent at least in part upon erratic rainfall. Rainfall limits reproduction, which in turn limits growth rate, but because the rainfall is unpredictable, it cannot regulate Agave populations. Can you think of some other factors like this?

Human activities, for example, act in this way. These include use of pesticides, such as DDT, and herbicides, and habitat destruction. See if you can think of explanations as to why these factors are considered density-independent factors.

We will next be examining the growth of human populations. What kind of growth rate do you think humans follow?

Growth of the Human Population

There are two major schools of thought about human population growth. One group of people, sometimes known as the "Neo-Malthusians," believes that human population growth cannot continue without dire consequences. Another group, the "Cornucopians," believes that the Earth can provide an almost limitless amount of natural resources and that technology can solve or overcome low levels of resources and degradation of the environment caused by the increasing population. Which do you think is correct?

If we look back again at the growth curves that we examined in the last two sections, we might ask ourselves if human growth resembles the exponential J-shaped model or the logistic S-shaped model? In other words, are we built, as a population, to keep growing and to use up all our resources, and thus become extinct, or will we efficiently use our resources so that the Earth can sustain our growth?

We don't know all the answers yet, but by looking at population growth through history and by examining population growth in different countries we may see some patterns emerge. For example, if we look at worldwide human population growth from 10,000 BCE through today, our growth, overall, resembles exponential growth, increasing very slowly at first, but later growing at an accelerating rate and which does not approach the carrying capacity.

However, by looking at different countries' population growth over history, we see more complexity. The history of human population growth can be divided into four stages and we can see snapshot views of these stages in countries today. Human populations pass through these four or five predictable stages of growth (**Table**2.3):

TABLE 2.3: The Stages of Human Population Growth

Stage of Human Population Growth	Description
Stage 1	Birth and death rates are high and population growth is stable (i.e. early human history)
Stage 2	Significant drop in death rate, resulting in an increasingly rapid rise in population size (exponential growth)(i.e. 18th and 19th century Europe)
Stage 3	Population size continues to grow
Stage 4	Birth rates equal death rates and populations become stable
Stage 5	Total population size may level off

In looking ahead to the future, projections by the United Nations and the US Census Bureau predict that by 2050, the Earth will be populated by 9.4 billion people. Other estimates predict 10 to 11 billion. The Cornucopians believe that more people are good for technology and innovation. The 5-stage model above predicts that when all countries are industrialized, the human population will eventually reach stability and a carrying capacity of sorts. However, many scientists and other Neo-Malthusians believe that humans have already gone over the Earth's carrying capacity for resources and habitat, and that this will eventually lead to famine, epidemics, or war, thus causing a population crash or even extinction.

Which of the above theories makes sense to you? What ways can you think of that people might use to avoid reaching Earth's carrying capacity?

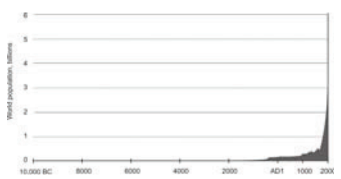


FIGURE 2.2
Worldwide human population growth from 10,000 BCE through today

Lesson Summary

- A population is comprised of organisms belonging to the same species, all living in the same area and interacting with each other
- One measure of a population's health is the dispersion of individuals within a population
- Information about birth rate, death rate, and survivorship curves also show how populations grow and change
- The population growth rate shows how the population size changes per population member per unit of time and depends on birth and death rates and migration
- There are different types of migrations that affect population density
- Under ideal conditions, populations show exponential growth; under more realistic conditions, limiting factors (density-dependent and density-independent factors) cause logistic growth
- There are two major schools of thought about human population growth; the Neo-Malthusians and the cornucopians

Review Questions

1. Name two ways in which ecologists can get an idea of the health of a population.
2. For a secretive or highly mobile species, how might you determine population size?
3. What might cause a clumped or clustered dispersion?

4. In an altricial reproductive strategy used by robins and hummingbirds, the birds hatch helpless and naked. Parents invest little energy in just a few, small eggs. It is important these offspring survive, because there are so few. What strategies might parents use to ensure that their young survive?
5. How does a limiting factor such as food supply limit population size?
6. In human history, major advances in technology caused an increase in carrying capacity. What do you think these major advances were?
7. Name some environmental crises that support the idea that our human population has already grown beyond the carrying capacity resulting in environmental degradation.

Points to Consider

- Now that you understand what makes up a population, what do you think makes up a community?
- You have learned about some of the factors that limit populations. What do you think are some interactions that affect the community?

2.3 Communities

Lesson Objectives

- Explain what a community is.
- Describe community interactions
- Explain what competition is and how it affects the community.
- Describe predation and how that affects prey density.
- Explain what symbiosis is and give examples of different kinds of symbiosis.

Check Your Understanding

- What is a population?
- How do density-dependent factors promote competition between members of the same population?

Introduction

Now that we have examined the dynamics of a single species at the population level, we are now ready to move to the next higher level. This is the community level, where we look at how populations of different species that occupy the same area interact with each other. As we will see, there are a number of types of interactions, including competition, predation and symbiosis. These interactions in turn affect the species' interactions with one another.

What is a Community?

A **community** is an assemblage within, the same area, of populations of different species interacting with each other. The term can be used in various ways with differences in meaning. For example, it may be limited to specific places, at specific times, or certain types of organisms. Thus, one may study the fish community in Lake Ontario or the fish in this lake during a specific period, such as the period before industrialization.

A community may also be defined according to the classification of and the geographic distribution of, species, as in an oak-hickory forest. On the other hand, a community might be defined according to function and behavior, as in a forest that is moderate in temperature (temperate) and sheds leaves annually (deciduous).

Community Interactions

Community interactions can be either intraspecific, that is between members of the same species, or interspecific, between members of different species. There are a number of different types of interactions, such as competition, predation, and symbiosis, which can be described as beneficial, detrimental or neutral. For example, competition could be looked at as having negative effects on the competing individuals or species, whereas mutualism, a type of symbiosis, could be seen as positive for the individuals involved.

As we examine different types of interactions in the next few sections, we will see more specifically why interactions are considered positive, negative, or neutral. We usually look at costs and benefits in terms of fitness, or survival and reproduction. These types of interactions may alter populations, communities, and even ecosystems, and the evolution of interacting species.

Competition

Competition can be defined as an interaction between organisms of the same or different species, in which the "fitness" of one is lowered by the presence of another. Individuals compete for a limited supply of at least one resource, such as food, water, or territory. Fitness refers to the ability of a species to survive and reproduce.

Competition can be described in terms of the mechanisms by which it occurs, either directly or indirectly. For example, competition may occur directly between individuals via aggression or some other means, whereby individuals interfere with survival, foraging or reproduction, or by physically preventing them from occupying an area of the habitat. Indirect competition is when a common limiting resource acts as an intermediate. For example, use of a specific resource or resources decreases the amount available to others, thereby affecting the others' fitness, or competition for space results in negatively affecting the fitness of one of the competing individuals.

Another type of indirect competition occurs when two species are preyed upon by the same predator. If the population size of one species increases, this would cause the predator population to increase, and might result in the other species' population size decreasing.

Intraspecific competition occurs when members of the same species compete for the same resources, like food, space, or light. Two organisms competing for the same resource can adapt to such conditions. Thus, if two trees growing close together are competing for light, water, and nutrients, one may supercede the other by growing taller to get more available light or develop a more extensive root system to get more water and nutrients. Such a situation results in survival for the organism that has better adapted to that environment.

Interspecific competition occurs when individuals of different species share a limiting resource in the same area, resulting in one of the species having lowered reproductive success, growth, or survival. For example, cheetahs and lions feed on similar prey. If prey is limited, then one species may catch more prey than the other and force the other species to leave the area. Lions sometimes steal prey killed by cheetahs. This could negatively affect the survival of the cheetahs.

According to the **competitive exclusion principle**, species less suited to compete for resources will either adapt, be excluded from the area, or die out. This is similar to what happens within a species. Evolutionary theory says that competition for resources within and between species plays an important role in natural selection (**Table** 2.4).

In order for two species within the same area to coexist, they may develop different strategies. This is known as **character displacement** and an example of this is the different feeding adaptations, such as bill structure, that developed in Darwin's Finches (**Figure**2.3).

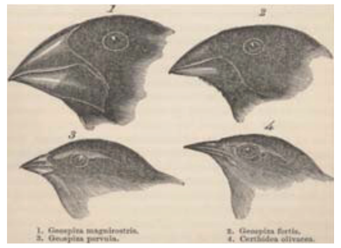


FIGURE 2.3

An example of character displacement, showing different bill structures, reflecting different feeding strategies, in Darwins or Galapagos Finches. From Darwins Journal, 1845, during the voyage of the H.M.S. Beagle.

TABLE 2.4: Main Features of Competition

Type of Competition	Description of Competition
Direct Competition	Occurs directly between individuals via aggression or some other means.
Indirect Competition	Occurs indirectly through a common limiting resource, which acts as an intermediate, and/or occurs between two species which are both preyed upon by the same predator.

TABLE 2.4: (continued)

Type of Competition	Description of Competition
Intraspecific Competition	Occurs when members of the same species compete for the same resources, like food, nutrients, space, or light.
Interspecific Competition	Occurs when individuals of different species share a limiting resource in the same area.

Predation

Predation (predator-prey relationship) is an interaction where a predator organism feeds on another living organism or organisms, known as prey. Predators may or may not kill their prey prior to eating them. The key characteristic of predation is the direct effect of the predator on the prey population.

In all classifications of predation, the predator lowers the prey's fitness, by reducing the prey's survival, reproduction, or both. Other types of consumption, like detritivory, where dead organic material (detritus) is consumed, have no direct impact on the population of the food source.

Predation can be classified in a number of different ways. One way is to classify it functionally, according to the extent to which the predators feed on and interact with their prey. This type includes true predation, grazing, and parasitism. (Parasitism will be discussed later in this lesson.)

True predation is the type in which the predator kills and eats its prey. Some predators of this type, such as jaguars, kill large prey and dismember or chew it prior to eating it (**Figure**2.4). Others, such as a bottlenose dolphin or snake, may eat its prey whole. In some cases, the prey dies in the mouth or digestive system of the predator. Baleen whales, for example, eat millions of plankton at once, with the prey being digested afterward. Predators of this type may actively pursue prey, or wait for it to approach to within striking distance.

FIGURE 2.4
An example of a true predator, showing a lioness actively hunting warthogs in the western corridor of the Serengeti, in Africa.

In **grazing**, the predator eats part of the prey, but rarely kills it. Many of this type of prey species are able to regenerate or regrow the grazed parts, so there is no real effect on the population. For example, most plants can regrow after being grazed upon by livestock. Kelp regrows continuously at the base of the blade to cope with browsing pressure. Starfish, also, can regenerate lost arms when they are grazed on. Parasites feed in a similar way to grazers, but are noted for their close association with their host species, and will be discussed further in the next section on symbiosis.

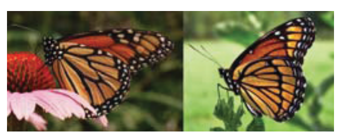


FIGURE 2.5
An example of Batesian mimicry, where the Viceroy butterfly () (right) mimics the unpalatable Monarch butterfly () (left). Both species are avoided by predators to a greater degree than either one would be otherwise.

Another way of classifying predators is by degree of specialization. Many predators, such as pandas and the snail kite, specialize in hunting only one species of prey, or certain classes of prey. Others, such as humans, leopards, and dogs, will kill and eat a wide variety of species. Specialists are usually well adapted in capturing their prey, but prey may be equally well adapted to escaping the predator. This helps to keep both populations in equilibrium. Almost

all specialists will usually successfully switch to other prey, or may resort to scavenging, or even a vegetarian diet, if the preferred prey is extremely scarce.

Predators play an ecological role, in that they may increase the biodiversity of communities by preventing a single species from becoming dominant, as in the grazers of a grassland. Introduction or removal of these dominant **keystone species**, or changes in its population density, can have drastic effects on the equilibrium of many other populations in the ecosystem.

The act of predation can be broken down into four stages: detection of prey, attack, capture, and consumption. At each stage, predator and prey have adaptations for obtaining food and avoiding predation (**Table** 2.5), respectively. One mechanism to avoid detection is **camouflage** (**Figure** 2.6), where species have an appearance (color, shape or pattern) which helps them blend into the background. Mimicry is a related phenomenon where a species uses appearance to copy another species, and which is used by both predators and prey (**Figure** 2.6).

TABLE 2.5: Main Features of Predation

Type of Predation	Description of Predation
True Predation	Predator kills and eats its prey
Grazing	Predator eats part of the prey, but rarely kills it
By degree of Specialization	Predator specializes in hunting only one species of prey, or certain classes of prey, or predator kills and eats a wide variety of prey species

FIGURE 2.6
Camouflage by the dead leaf mantis, , makes it less visible to both its predators and prey. If alarmed, it lies motionless on the rainforest floor of Madagascar, Africa, camouflaged among the actual dead leaves. It eats other animals up to the size of small lizards.

Anti-predatory Adaptations

Camouflage	Species have an appearance which helps them blend into background
Mimicry	Species uses appearance to copy another species, and is used by both predators and prey

Symbiosis

The term **symbiosis** commonly describes close and often long-term interactions between different species, in which at least one species benefits. The symbiotic relationship may be characterized as being mutualistic, commensalistic, or parasitic. In **mutualism**, both species benefit; in **commensalism**, one species benefits while the other is not affected; and in **parasitism**, the parasitic species benefits, while the host species is harmed.

Competition (-, -)

Elk and deer compete for the same food resources.

Symbiotic Relationships

Mutualism (+,+)	Both species benefit.
Commensalism (+, O)	One species benefits, while the other is not affected.
Parasitism (+, -)	Parasitic species benefits, while host species is harmed.

Mutualistic relationships include the large percentage of herbivores that have gut fauna that help them digest plant matter, coral reefs that have various types of algae living inside, and the relationship between the Ocellaris clownfish and the Ritteri sea anemones. In the latter example, the clownfish protects the anemone from anemone-eating fish, and in turn, the stinging tentacles of the anemone protect the clownfish from its predators (**Figure** 2.7).

Commensal relationships may involve an organism using another for transportation or housing, such as spiders building their webs on trees, or may involve an organism using something another created, after the death of the first.

Parasites include those that either live within the host's body, such as hookworms, or those that live on its surface, such as lice. In addition, parasites may either kill the host they live on, or rely on the host's surviving. Parasites are found not only in animals but also in plants and fungi.

FIGURE 2.7

A mutualistic relationship between the Ocellaris clownfish and the Ritteri sea anemone. Myako Island, Japan. The fish protects the anemone from anemone-eating fish and the anemone protects the clownfish from its predators, with its stinging tentacles. The clownfish has a special mucus which protects it from the tentacles.

Lesson Summary

- A community is an assemblage within the same area, of populations of different species interacting with one another.
- Community interactions include competition, predation, and symbiosis.
- Competition can be either direct or indirect.
- Intra- and inter-specific competition occur when individuals share a limiting resource in the same area.
- The competitive exclusion principle plays an important role in natural selection.
- Functional types of predation include true predation, grazing, and parasitism.
- Predators can also be classified by degree of specialization.
- Prey use different adaptations to avoid detection, attack and capture by predators.
- Symbiosis includes mutualism, commensalism, and parasitism.

Review Questions

1. Define competition.
2. If the geographic distributions of two similar species do not overlap, would you expect the two species to have character displacement? Why or why not?
3. Observations of natural populations and manipulative experiments show that two recently evolved species of threespine stickleback fish (*Gasterosteus* spp.) show two distinct morphologies and feeding strategies in order to co-exist in the post-glacial lakes in which they live in western Canada. Morphologically they differ in the size, shape and the number and length of gill rakers, structures used in their feeding. Name two ways in which these fish species could use different feeding strategies in order to co-exist.
4. How might a predator lower a prey's fitness?
5. In most types of grazing, does the predator lower a prey's fitness? Why or why not?
6. A drone fly looks a lot like a bee, yet it is completely harmless as it cannot sting at all. What anti-predator mechanism is the drone fly using? Would you expect predators to always avoid drone flies?
7. In the mutualistic relationship between the Ocellaris clownfish and the Ritteri sea anemones, what benefit does the fish get?

8. Hosts may evolve defenses against their parasites. In turn, parasites evolve in response to these defense mechanisms, including evolving adaptations that are specific to a particular host taxon, even specializing to the point at which they infect only a single species. How might such narrow host specificity be costly over evolutionary time? What would help to reduce this cost?

Point to Consider

- How are predators dependent on prey and vice-versa?

2.4 Ecosystems

Lesson Objectives

- Explain what an ecosystem is.
- Discuss how biotic and abiotic factors play a role in the ecosystem.
- Explain what a niche is and its importance in an ecosystem.
- Describe what a habitat is and how an organism is adapted to live in the habitat.

Check Your Understanding

- What is a community?
- What are the different types of community interactions?

Introduction

Now that you have studied what a community is, you have seen some of the interactions that occur between species. The next level, the ecosystem, includes not only the biological components, but also the abiotic components, all functioning together. You will examine in more depth biotic and abiotic factors, and how the concepts of the niche and habitat play important roles in the ecosystem.

What is an Ecosystem?

An **ecosystem** is a natural unit consisting of all the biotic factors (plants, animals and micro-organisms) functioning together in an area along with all of the abiotic factors (the non-living physical factors of the environment). The concept of an ecosystem can apply to a large body of freshwater, for example, as well as a small piece of dead wood. Other examples of ecosystems include the coral reef, the Greater Yellowstone ecosystem, the rainforest, the savanna, the tundra, the desert and the urban ecosystem (**Figure**2.8).

FIGURE 2.8
An example of a desert ecosystem, a desert in Baja California, showing Saguaro cactus.

Ecosystems, like most natural systems, depend on continuous input of energy from outside the system, mostly in the form of sunlight. In addition to energy's being transferred within the ecosystem, matter is recycled. Thus, elements such as carbon and nitrogen, and water, all needed by living organisms, are used over and over again.

Ecosystems can be discussed with respect to humans as well. A system as small as a household, neighborhood, or college, or as large as a nation, may then be suitably discussed as a human ecosystem. While they may be bounded and individually discussed, human ecosystems do not exist independently, but interact in a web of complex human and ecological relationships connecting all human ecosystems.

Since humans touch virtually all surfaces of the earth today, all ecosystems can be more accurately considered as human ecosystems. In 2005, the largest assessment ever conducted of the earth's ecosystems was done by a research team of over 1,000 scientists. The study concluded that in the past 50 years, humans have altered the earth's ecosystems more than any other time in our history.

Biotic and Abiotic Factors

Biotic factors of an ecosystem include all living components, from bacteria and fungi, to unicellular and multicellular plants, to unicellular and multicellular animals. **Abiotic factors** are non-living chemical and physical factors in the environment. The six major abiotic factors are water, sunlight, oxygen, temperature, soil and climate (such as humidity, atmosphere, and wind). Other factors which might also come into play are other atmospheric gases, such as carbon dioxide, and factors such as physical geography and geology.

Abiotic and biotic factors not only interrelate within an ecosystem but also between ecosystems. For example, water may circulate between ecosystems, by the means of a river or ocean current, and some species, such as salmon or freshwater eels, move between marine and freshwater systems.

Niche

One of the most important ideas associated with ecosystems is the **niche** concept. A niche refers to the role a species or population plays in the ecosystem, with respect to all the interactions with its abiotic and biotic components. A shorthand definition is that a niche is how an organism "makes a living". Some of the important aspects of a species' niche are the food it eats, how it obtains the food, nutrient requirements, space, etc.

The different dimensions of a niche represent different biotic and abiotic variables. These factors may include descriptions of the organism's life history, habitat, trophic position (place in the food chain), and geographic range.

Different species can hold similar niches in different locations, and the same species may occupy different niches in different locations. Species of the Australian grasslands, although different from those of the Great Plains grasslands, occupy the same niche.

Once a niche is left vacant, other organisms can fill in that position. When the tarpan (a small, wild horse, chiefly of southern Russia) became extinct in the early 1900s, the niche it left vacant as filled by other animals, in particular a small horse breed, the konik (**Figure** 2.9).

FIGURE 2.9
The konik horse, which filled the niche left vacant by the tarpan, a horse that became extinct in the early 1900s in southern Russia.

When plants and animals are introduced, either intentionally or by accident, into a new environment, they can occupy the new niches or niches of native organisms, and sometimes outcompete the native species, and become a serious pest. For example, kudzu, a Japanese vine, was introduced intentionally to the southeastern United States in the 1870s to help control soil erosion. Kudzu had no natural enemies there and was able to outcompete native species of vines and take over their niches (**Figure** 2.10).

FIGURE 2.10
Kudzu, a Japanese vine, introduced intentionally to the southeastern United States, has outcompeted the native vegetation.

As already discussed in the Communities lesson, the competitive exclusion principle states, that if niche overlap occurs, either one species will be excluded, character displacement will occur (as in Darwin's Finches), or extinction occurs.

Habitat

The **habitat** is the ecological or environmental area in which a particular species lives; the physical environment to which it has become adapted and in which it can survive (**Figure**211). A habitat is generally described in terms of abiotic factors, such as the average amount of sunlight received each day, the range of annual temperatures, and average yearly rainfall. These and other factors determine the kind of traits an organism must have in order to survive there (**Figures** 2.12 and 2.13).

FIGURE 2.11
Santa Cruz, the largest of the northern Channel Islands, has the most diverse of habitats in the sanctuary, including a coastline with steep cliffs, coves, gigantic caves, and sandy beaches.

FIGURE 2.12
Another example of a type of habitat, showing a meadow and representative vegetation.

FIGURE 2.13
Winter flock of Bearded Reedlings in their natural habitat of dense wetland reeds, in Helsinki, Finland

Habitat destruction is a major factor in causing a species population to decrease, eventually leading to its being endangered or even going extinct. Large scale land clearing usually results in the removal of native vegetation and

habitat destruction. Poor fire management, pest and weed invasion, and storm damage can also destroy habitat. National parks, nature reserves, and other protected areas all provide adequate refuge for organisms by preserving habitats.

Habitats can also be examined from a human point of view. Thus, it is the environment in which humans live, work, recreate, and move about. Human habitat is the sum total of all factors which constitute the total environment where humans live, work, and perform their essential and day-to-day obligations.

Lesson Summary

- An ecosystem is a natural unit consisting of all the biotic and abiotic factors functioning together in an area.
- Biotic factors include all living components of an ecosystem and abiotic factors are the non-living chemical and physical factors in the environment.
- There are six major abiotic factors.
- The niche concept is one of the most important ideas associated with ecosystems.
- If niche overlap occurs, then the competitive exclusion principle comes into play.
- The habitat is the area where a particular species, species population, or community lives.
- Habitat destruction is a major cause of population decrease, leading to possible extinction.
- Both the ecosystem and habitat can be looked at from a human point of view.

Review Questions

1. Give three examples of ecosystems.
2. List three abiotic components of importance to trees living in a forest.
3. Give an example of an organism filling a vacant niche.
4. Why might an introduced species become a pest?
5. How could separation of breeding periods in frogs result in niche differentiation in the tadpoles?
6. Name three abiotic factors that a habitat is generally described in terms of.
7. Species which travel distances between important areas for their survival, such as breeding and feeding areas may be particularly vulnerable to habitat destruction. How might the creation of multiple national parks or nature reserves help such species?

Points to Consider

- Now that you understand what makes up an ecosystem, what additional factors do you think might be added to get to the next level, the biome?
- How do you think what you have learned about abiotic and biotic factors might be applied to the classification of different biomes?
- The biosphere is considered to be a global ecological system. Given all you now know about ecology, what do you think the biosphere consists of?

2.5 Biomes and the Biosphere

Lesson Objectives

- Explain what biomes are.
- Describe the features of the biosphere and list specific systems.

Check Your Understanding

- What is an Ecosystem?
- How can Ecosystems be discussed with respect to Humans?

Introduction

The concept of biomes and the largest biome of all, the biosphere, is the highest level of organization in ecology, building on everything you have already studied at the population, community, and ecosystem levels. There is a wide variety of biomes, classified into two major groups, terrestrial and aquatic biomes. Because the biosphere integrates all living beings, and can be considered itself a kind of living organism, human activities on one part of Earth can have a major effect on another. In order to better understand all the interactions on Earth, scientists have created various small-scale models.

What are Biomes?

A **biome** is a climatically and geographically defined area of ecologically similar communities of plants and animals, often referred to as ecosystems. Biomes are often identified with particular patterns of ecological succession and climax vegetation.

Biome type may also be based on differences of the physical environment (for example, mountain ranges or oceans). Their variation is generally related to the distribution of species according to their ability to tolerate temperature and/or dryness. For example, one may find photosynthetic algae only in the part of the ocean where light penetrates, while conifers are mostly found in mountains.

The biodiversity characteristic of each biome, especially the diversity of fauna and subdominant plant forms, is a function of abiotic factors and the biomass productivity of the dominant vegetation. Species diversity tends to be higher in terrestrial biomes with higher net primary productivity, moisture availability, and temperature. Biodiversity also generally increases most rapidly near the equator and less rapidly toward the poles, and increases with humidity.

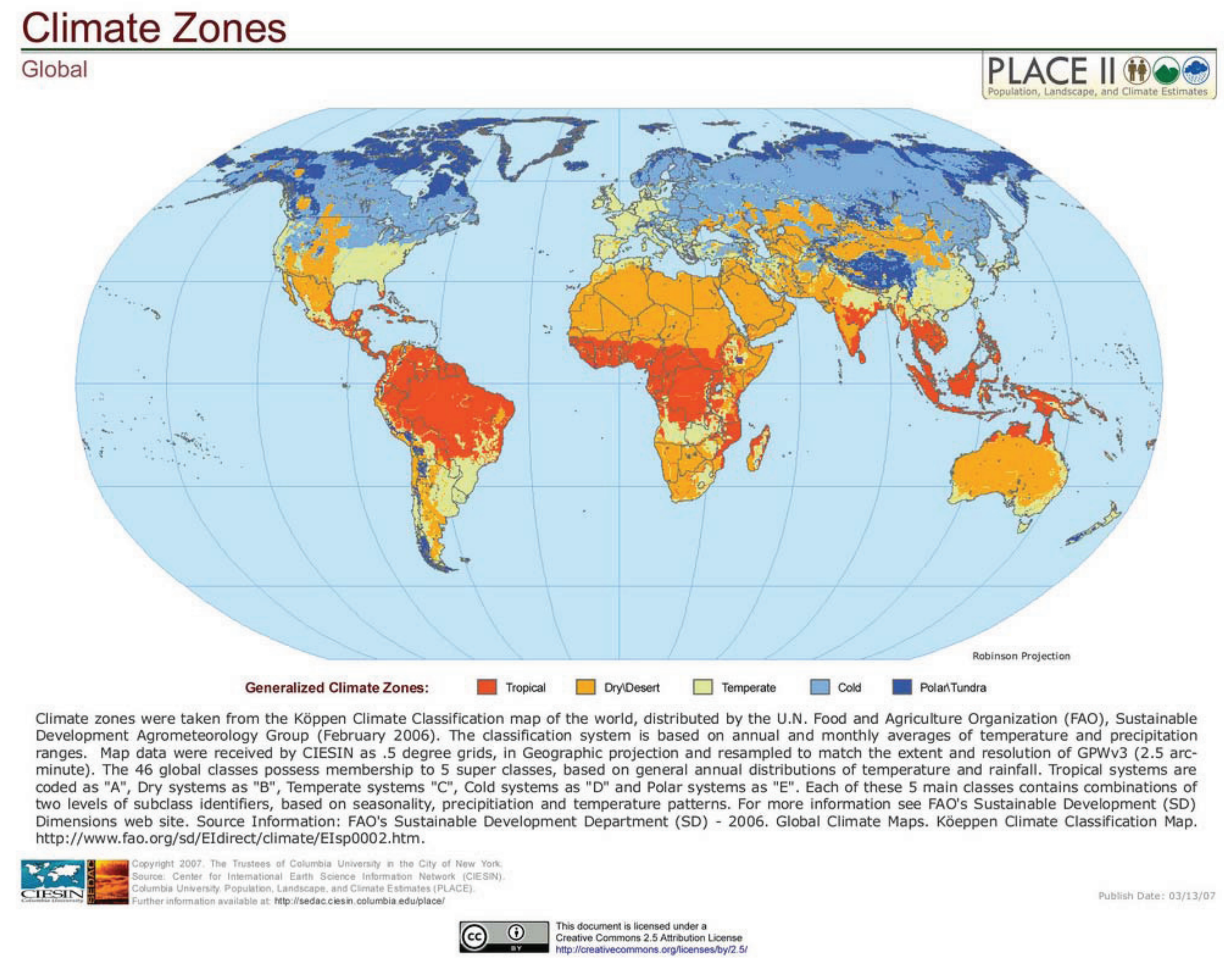


FIGURE 2.14

Types of Terrestrial Biomes:

Tundra:

Taiga:

Deciduous Forests:

Deserts:

Grasslands:

Tropical Rain Forests:

Terrestrial biomes are defined based on factors such as plant structures (such as trees, shrubs, and grasses), leaf types (such as broadleaf and needleleaf), and plant spacing (forest, woodland, savanna). Climate is also a major factor determining the distribution of terrestrial biomes. Among the important climatic factors are latitude, from the poles to the equator (Arctic, boreal, temperate, subtropical, tropical); humidity (humid, semi-humid, semi-arid, and arid), with seasonal variation in rainfall; and elevation (increasing elevation causes a distribution of habitat types similar to that of increasing latitude) (**Table** 2.6). Terrestrial biomes (**Figure** 2.14) that lie within the Arctic and Antarctic Circles are relatively barren of plant and animal life, while most of the more populous biomes lie near the

equator (**Figure** 2.16).

FIGURE 2.15
One of the terrestrial biomes, a taiga, a coniferous evergreen forest of the subarctic, covering extensive areas of northern North America and Eurasia. This taiga is along the Denali Highway in Alaska. The Alaska Range is in the background.

FIGURE 2.16
A terrestrial biome, a tropical rainforest, located in the Amazon basin north of Manaus, Brazil. The image was taken 30 minutes after a rain event, and a few white clouds above the canopy are indicative of rapid evaporation from wet leaves after the rain.

TABLE 2.6: **Characteristics of Terrestrial Biome**

Characteristics of Terrestrial Biome	Description of Characteristics
Plant structures	Trees, shrubs, grasses
Leaf types	Broadleaf, needleleaf
Plant spacing	Forest, woodland, savanna
Latitude from poles to the equator	Arctic, boreal, temperate, subtropical, tropical
Humidity	Humid, semi-humid, semi-arid, arid
Elevation	Increasing elevation causes habitat changes similar to that of increasing latitude

Aquatic biomes (which also can be classified into freshwater and marine biomes) can be defined according to:

- size
- depth, such as the continental shelf
- vegetation, such as a kelp forest
- animal communities
- other physical characteristics, including pack ice or hydrothermal vents

The Biosphere

The most inclusive level of organization in ecology is the **biosphere**. It is the part of the Earth, including air, land, surface rocks, and water, within which life occurs, and which biotic processes in turn alter or change. It is the global ecological system integrating all life forms and their relationships, including their interactions with the outer layer of the earth: the lithosphere (or sphere of soils and rocks), hydrosphere (or sphere of water) and atmosphere (or sphere of the air). The biosphere occurs in a very thin layer of the planet, extending from about 11,000 meters below sea level to 15,000 meters above sea level and reaches well into the other three spheres.

For a better understanding of how the biosphere works and various dysfunctions related to human activity, scientists have simulated the biosphere in small-scale models. Biosphere 2 (**Figure** 2.17) is a laboratory in Arizona which contains 3.15 acres of closed ecosystem BIOS-3 was a closed ecosystem in Siberia; and Biosphere J is located in Japan.

FIGURE 2.17
Biosphere 2, in Arizona, contains 3.15 acres of closed ecosystem and is a small-scale model of the biosphere.

Direct human interactions with ecosystems, including agriculture, human settlements, urbanization, forestry, and other uses of land, have fundamentally altered global patterns of biodiversity and ecosystem processes. As a result, vegetation patterns predicted by conventional biome systems are rarely observed across most of the planet's land surface. In terms of the human impact on biomes and ecosystems, the study of ecology is now more important than ever. Scientists that study ecology will move us toward an understanding of how best to live in and manage our biosphere.

Lesson Summary

- A biome is a climatically and geographically defined area of ecologically similar communities of plants and animals
- Biomes are classified in different ways, sometimes according to patterns of ecological succession and climax vegetation, other times according to differences in the physical environment, and in other situations according to latitude and humidity
- Biodiversity of each biome is a function of abiotic factors, such as moisture availability and temperature, and the biomass productivity of the dominant vegetation
- Terrestrial biomes are defined based on various plant factors and on climate
- Aquatic biomes are classified according to various factors and further subdivided into freshwater and marine biomes
- The most inclusive level of organization in ecology is the biosphere and it is a global ecological system
- The biosphere is itself a living organism.
- Humans have fundamentally altered global patterns of biodiversity and ecosystem processes

Review Questions

1. Define a biome.
2. Name a type of biome based on the physical environment.
3. Where would you expect to find more biodiversity, in an equatorial rainforest, or in a southwestern desert? Explain why.
4. Which classification scheme is used to define ecoregions as priorities for conservation?
5. As you climb a mountain, you will see the vegetation and habitat type change. How could you see a similar change of habitat types if you were traveling geographically?
6. Water is exchanged between the hydrosphere, lithosphere, atmosphere, and biosphere in regular cycles. What role do the oceans play in the biosphere?

Points to Consider

You now have a general idea of what a biome is and how the diversity of a biome is related to other factors; the next chapter, on ecosystem dynamics, will give you a greater understanding of how energy flow, cycling of matter, and succession vary from one biome to another

- One of the aquatic biomes, the hydrothermal vents, mentioned previously in this chapter, is not dependent on sunlight but on bacteria, which utilize the chemistry of the hot volcanic vents. See if you can guess where these bacteria fit into the flow of energy in an ecosystem.

2.6 Flow of Energy

Lesson Objectives

- Explain where all the energy in an ecosystem ultimately comes from.
- Classify organisms on the basis of how they obtain energy (producers, consumers, and decomposers) and describe examples of each.
- Be able to draw and interpret a food web.
- Explain the flow of energy through an ecosystem using an energy pyramid.
- Compare the relative energy output expended by an organism in obtaining food to the energy gained from the food.

Check Your Understanding

- What is photosynthesis?
- What are some examples of organisms that can photosynthesize?
- What is a community?

Introduction

Energy is defined as the ability to do work. In organisms, this work can involve not only physical work like walking or jumping, but also carrying out the essential chemical reactions of our bodies. Therefore, all organisms need a supply of energy to stay alive. Some organisms can capture the energy of the sun, while others obtain energy from the bodies of other organisms. Through predator-prey relationships, the energy of one organism is passed on to another. Therefore, energy is constantly flowing through a community. Understanding how this energy moves through the ecosystem is an important part of the study of ecology.

Energy and Producers

With just a few exceptions, all life on Earth depends on the sun's energy for survival. The energy of the sun is first captured by **producers**(**Figure** 2.18), organisms that can make their own food. Many producers make their own food through the process of photosynthesis. Producers make or "produce" food for the rest of the ecosystem. Therefore the survival of every ecosystem is highly dependent on the stability of the producers. Without producers capturing the energy from the sun and turning it into "food," an ecosystem could not exist. In addition, there are bacteria that use chemical processes to produce food, getting their energy from sources other than the sun, and these are also considered producers.

There are many types of photosynthetic organisms that produce food for ecosystems. On land, plants are the dominant photosynthetic organisms. Algae are common producers in aquatic ecosystems. Single celled algae and tiny multicellular algae that float near the surface of water and that photosynthesize are called phytoplankton.

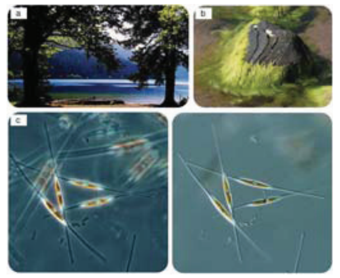


FIGURE 2.18
Producers include plants (a), algae (b), and diatoms, which are unicellular algae(c).

Although producers might look quite different from one another, they are similar in that they make food containing complex organic compounds, such as fats or carbohydrates, from simple inorganic ingredients. Recall that the only required ingredients needed for photosynthesis are sunlight, carbon dioxide (CO_2), and water (H_2O). From these simple inorganic building blocks, photosynthetic organisms can produce glucose ($C_6H_{12}O_6$) and other complex organic compounds.

Consumers and Decomposers

Many types of organisms are not producers and cannot make their own food from sunlight, air, and water. The animals that must consume other organisms to get food for energy are called **consumers**. The consumers can be placed into several groups of heterotrophs. **Herbivores** are animals that eat photosynthetic organisms to obtain energy. For example, rabbits and deer are herbivores that eat plants. The caterpillar in **Figure** 2.19 is a herbivore. Animals that eat phytoplankton in aquatic environments are also herbivores. **Carnivores** feed on animals, either the herbivores or other carnivores. Snakes that eat mice are carnivores, and hawks that eat the snakes are also carnivores. See figure 2.19. **Omnivores** eat both producers and consumers. Most people are omnivores since they eat fruits, vegetables, and grains from plants and also meat and dairy products from animals. Dogs, bears, and raccoons are also omnivores.

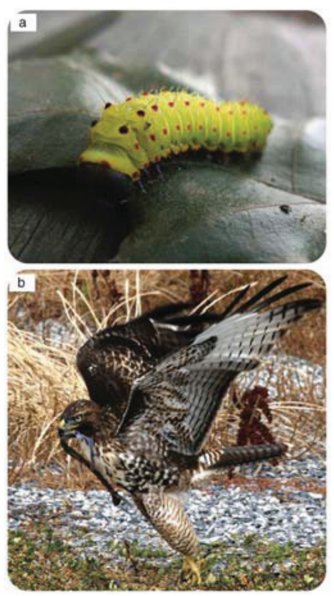


FIGURE 2.19
Examples of consumers are caterpillars (herbivores) and hawks (carnivore).

Decomposers (**Figure** 2.20) obtain nutrients and energy by breaking down dead organisms and animal wastes. Through this process, decomposers release nutrients, such as carbon and nitrogen, back into the ecosystem so that the producers can use them. Through this process these essential nutrients are recycled, an essential role for the survival of every ecosystem. Therefore, as with the producers, the stability of an ecosystem also depends on the

actions of the decomposers. Examples of decomposers include mushrooms on a decaying log and bacteria in the soil. Decomposers are essential for the survival of every ecosystem. Imagine what would happen if there were no decomposers. Wastes and the remains of dead organisms would pile up and the nutrients within the waste and dead organisms would never be released back into the ecosystem!

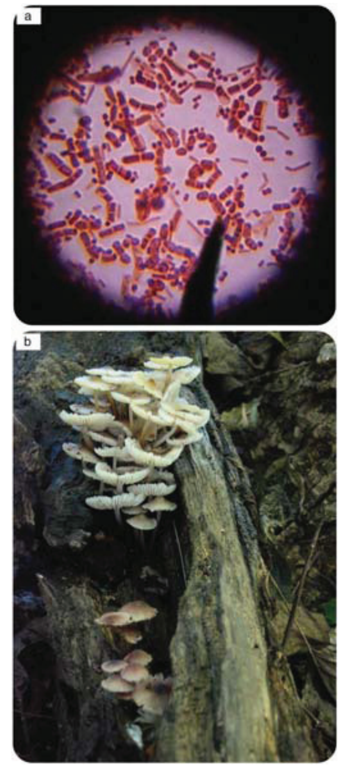


FIGURE 2.20
Examples of decomposers are bacteria (a) and fungi (b).

Food Chains and Food Webs

Food chains (**Figure** 2.21) are a visual representation of the eating patterns in an ecosystem, depicting how food energy flows from one organism to another. Arrows are used to indicate the feeding relationship between the animals. For example, an arrow from the leaves to a grasshopper shows that the grasshopper eats the leaves, so energy and nutrients are moving from the leaves to the grasshopper. Next, a mouse might prey on the grasshopper, a snake may eat the mouse, and then a hawk might eat the snake.

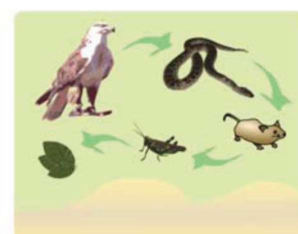


FIGURE 2.21
Food chain. This figure shows, for example, that the snake gets its energy from the rat, and the rat gets its energy from the insect.

In an ocean ecosystem, one possible food chain might look like this: phytoplankton -> krill -> fish -> shark. The producers are always at the beginning of the food chain, followed by the herbivores, then the carnivores. In this example, phytoplankton are eaten by krill, which are tiny shrimp-like animals. The krill are in turn eaten by fish, which are then eaten by sharks. Each organism can eat and be eaten by many different other types of organisms,

so simple food chains are rare in nature. There are also many different species of fish and sharks. Therefore, many food chains exist in each ecosystem

Since feeding relationships are so complicated, we can combine food chains together to create a more accurate depiction of the flow of energy within an ecosystem. A **food web** (**Figure** 2.22) shows the complex feeding relationships between many organisms in an ecosystem. If you expand our original example of a food chain, you might also include that deer also eat clover and foxes that also hunt chipmunks. A food web shows many more arrows but follows the same principle; the arrows depict the flow of energy (**Figure** 2.23). A complete food web may show hundreds of different feeding relationships.

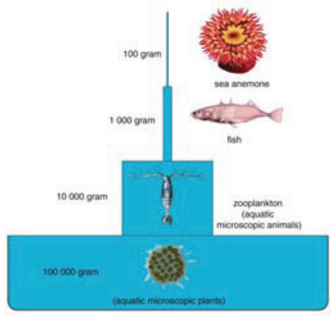


FIGURE 2.22
Food web in the Arctic Ocean. As illustrated by this ecological pyramid, it takes a lot of phytoplankton to support the carnivores of the oceans.

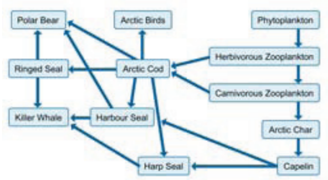


FIGURE 2.23
Food web in the Arctic Ocean.

Energy Pyramids

When an herbivore eats a plant, the energy that is stored in the plant tissues is used by the herbivore to power its own life processes and to build more body tissues. Only about 10% of the total energy from the plant gets stored in the herbivore's body as extra body tissue. The rest of the energy is transformed by the herbivore through metabolic activity and released as heat. The next consumer on the food chain that eats the herbivore will only store about 10% of the total energy from the herbivore in its own body. This means the carnivore will store only about 1% of the total energy that was originally in the plant. In other words, only about 10% of energy of one step in a food chain is stored in the next step in the food chain.

Every time energy is transferred from one organism to another, there is a net loss of energy. This loss of energy can be shown in an energy pyramid. An example of an energy pyramid is shown in **Figure 2.23**. Due to the energy loss in food chains, it takes many producers to support just a few carnivores in a community. For example, there are far fewer hawks than acorns in this food chain.

Each step of the food chain reflected in the ecological pyramid is called a **trophic level**. Plants or other photosynthetic organisms are found on the first trophic level, at the base of the pyramid. The next level would be the herbivores, then the carnivores that eat the herbivores. The energy pyramid in **Figure** 2.22 shows only three levels of a food chain, from plants (producers) to hawks (carnivores). Because of the high rate of energy loss in food chains, there are usually only 4 or 5 levels in the chain or energy pyramid.

Compare the relative energy output expended by an organism in obtaining food to the energy gained from the food. Humingbirds have to expend energy in order to obtain nectar for metabolic energy. Can you think of any other

examples of comparing energy output to food intake?

Lesson Summary

- Producers, which include photosynthetic organisms like plants and algae, can make their own food from simple inorganic compounds.
- Consumers must obtain their nutrients and energy by eating other organisms, while decomposers break down animal remains and wastes to obtain energy.
- Food chains and food webs are visual representations of feeding patterns in an ecosystem.
- As energy is transferred along a food chain, energy is lost as heat.

Review Questions

1. How do decomposers obtain energy?
2. What happens to 90% of the energy that passes from one step in the food chain to the next step?
3. For #'s 3 - 5, Analyze the following food chain: algae -> fish -> herons
4. What is the producer in the food chain?
5. What is the herbivore in the food chain?
6. What is the carnivore in the food chain?
7. In a food chain, does the prey or predator have a greater biomass?
8. In an ecological pyramid, which level would have the greatest biomass?
9. What is the term for the visual representation of complex feeding interactions in a community?
10. In a forest community, caterpillars eat leaves, and birds eat caterpillars. Draw the food chain.
11. What's the term for a consumer that eats both plants and animals?

Points to Consider

- Animals are carbon-based organisms. When animals decompose, what happens to the carbon? Discuss this with your class.
- We need nitrogen to make our DNA. Where does it come from? Where does it go? What would happen to nitrogen released from decaying organisms?
- Water is essential for photosynthesis. Water moves through both the living and non-living parts of an ecosystem. How does water move through the living parts of an ecosystem?

2.7 Cycles of Matter

Lesson Objectives

- Describe the key features of the water cycle.
- Describe the key features of the nitrogen cycle.
- Describe the key features of the carbon cycle.
- Describe the key features of the phosphorus cycle
- Describe the key features of the oxygen cycle

Check Your Understanding

- What types of organisms break down animal remains and wastes to release nutrients?
- What are the main chemical elements that are essential for life?

Introduction

What happens to all the plants and animals that die? Do they pile up and litter ecosystems with dead remains? Or do they decompose? The role of decomposers in the environment often goes unnoticed, but these organisms are absolutely crucial for every ecosystem. Imagine if the decomposers were somehow taken out of an ecosystem. The nutrients, such as carbon and nitrogen, in animal wastes and dead organisms would remain locked in these forms if there was nothing to decompose them. Overtime, almost all the nutrients in the ecosystem would be used up. However, these elements are essential to build the organic compounds necessary for life and so they must be recycled. The decomposition of animal wastes and dead organisms allows these nutrients to be recycled and re-enter the ecosystem, where they can be used by living organisms.

The pathways by which chemicals are recycled in an ecosystem are **biogeochemical cycles**. This recycling process involves both the living parts (biotic) of the ecosystem and the non-living (abiotic) parts of the ecosystem, such as the atmosphere, soil, or water. The same chemicals are constantly being passed through living organisms to non-living matter and back again, over and over. Through biogeochemical cycles, inorganic nutrients that are essential for life are continually recycled and made available again to living organisms. These recycled nutrients contain the elements carbon and nitrogen. Water is obviously an extremely important aspect of every ecosystem. Life could not exist without water. Water is also cycled through the biotic and abiotic factors of an ecosystem.

The Water Cycle

Since many organisms contain a large amount of water in their bodies, and some even live in water, the water cycle is essential to life on earth. Water is continually moving between living things and non-living things such as clouds, rivers, or oceans. The water cycle is also important because water is a solvent, so it plays an important role in dissolving minerals and gases and carrying them to the ocean. Therefore, the composition of the oceans is also dependent on the water cycle (**Figure** 2.24).

The water cycle does not have a real starting or ending point, since it is an endless circular process; however, we will start with the oceans. Water **evaporates** from the surface of the oceans, leaving behind salts. As the water vapor rises, it collects and is stored in clouds. As water cools in the clouds, it condenses into **precipitation** such as rain, snow, hail, sleet, etc. The precipitation allows the water to return again to the Earth's surface. On land, the water

can sink into the ground to become part of our underground water reserves, also known as**groundwater**. Much of this underground water is stored in **aquifers**, which are porous layers of rock that can hold water. Most precipitation that occurs over land, however, is not absorbed by the soil and is called **runoff**. This runoff collects in streams and rivers and moves back into the ocean.

Water also moves through the living organisms in the ecosystem. Plants are especially significant to the water cycle because they soak up large amounts of water through their roots. The water then moves up the plant and evaporates from the leaves in a process called transpiration. The process of **transpiration**, like evaporation, returns water back into the atmosphere.

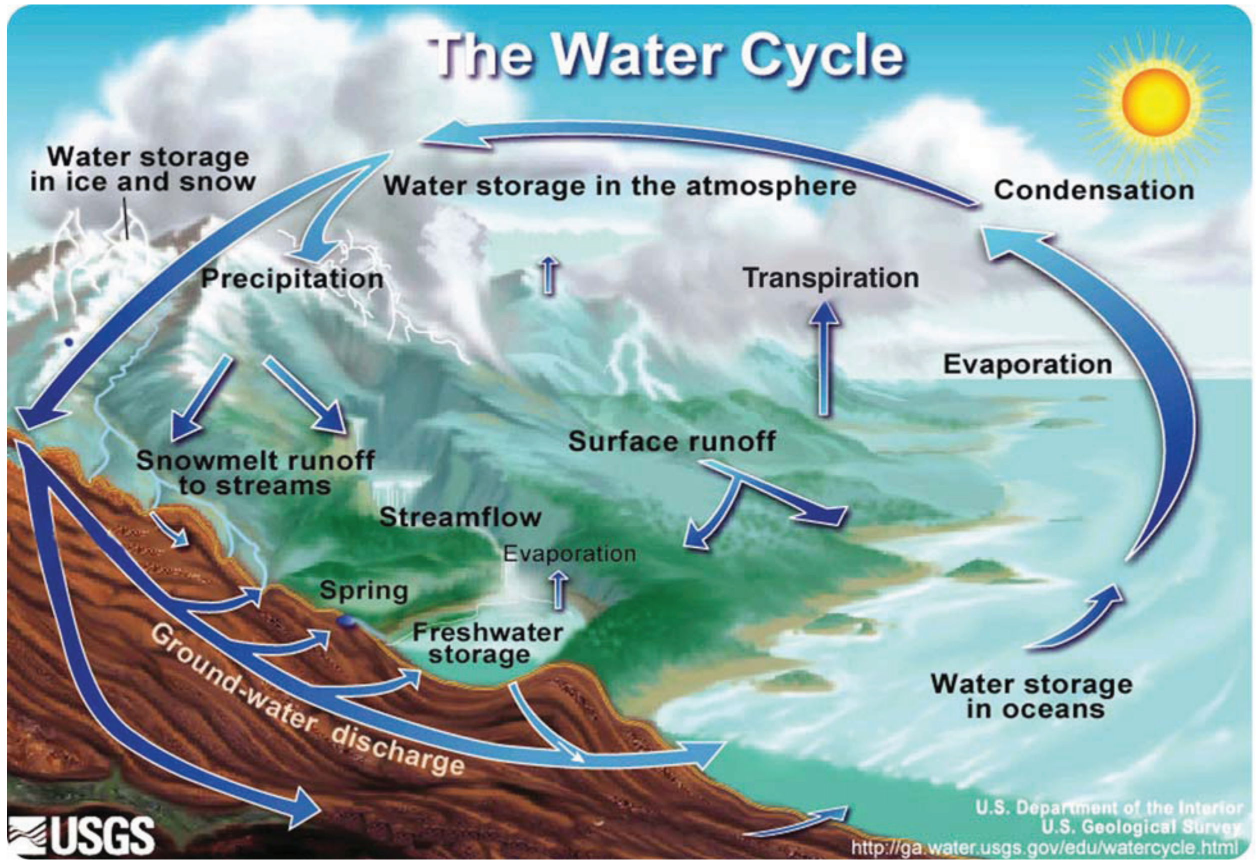


FIGURE 2.24
The water cycle. See for an animation of the water cycle.

Carbon Cycle

Runoff, streams, and rivers can gradually dissolve carbon in rocks and carry it to the ocean. The ocean is a major reservoir for stored carbon. It is just one of four major reservoirs. The other three are the atmosphere, the biosphere, and organic sediments such as fossil fuels. Fossil fuels, including petroleum and coal, form from the remains of dead organisms. All of these reservoirs of carbon are interconnected by pathways of exchange in the carbon cycle, which is shown in **Figure** below.

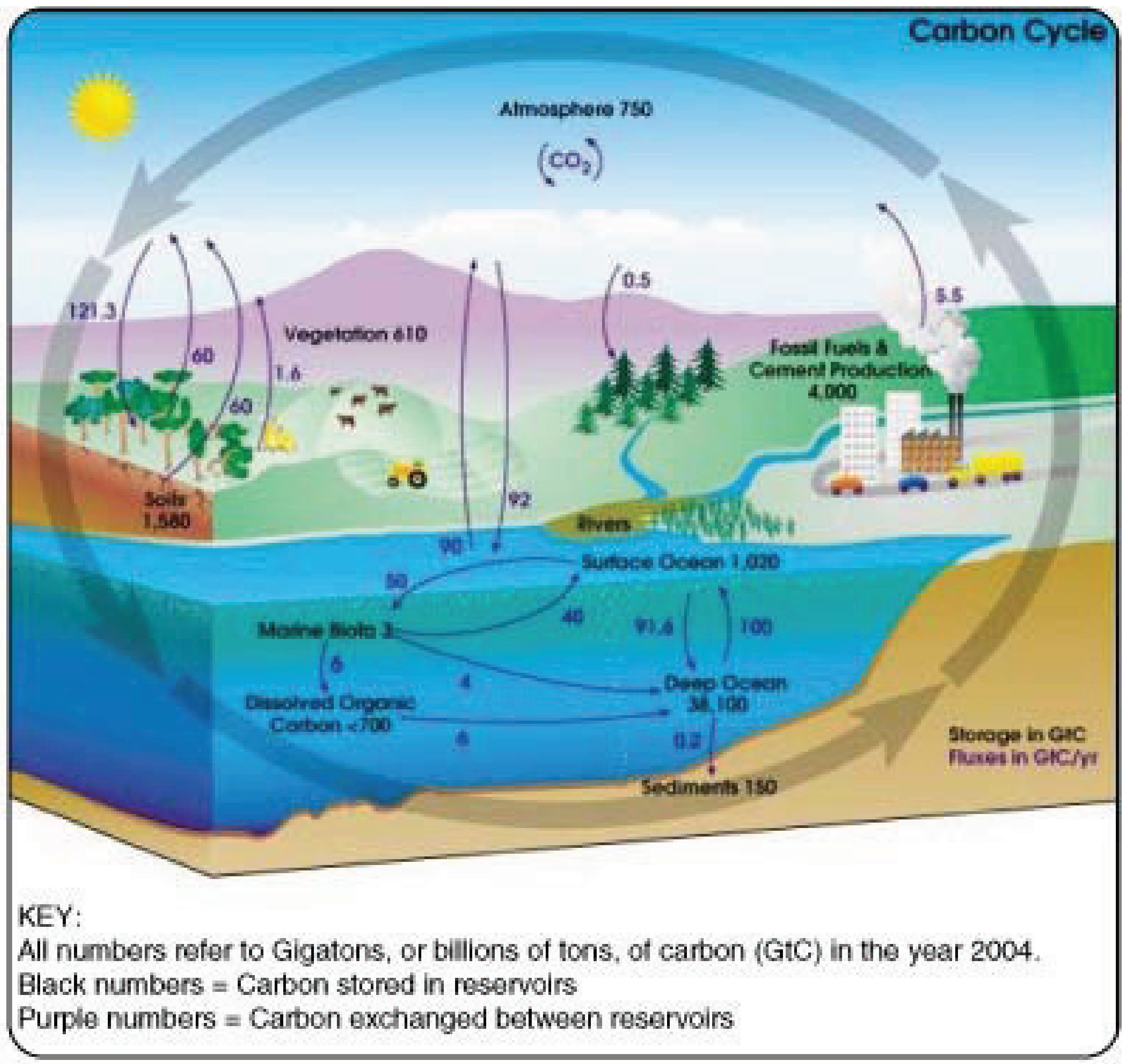


FIGURE 2.25
The Carbon Cycle

Carbon occurs in a various forms in different parts of the carbon cycle. Some of the different forms in which carbon appears are described in**Table** 2.7. Refer to the table as you read how carbon moves between reservoirs of the cycle.

TABLE 2.7: Forms of Carbon in the Carbon Cycle: Carbon Dioxide, Gas, Calcium Carbonate, Solids

Form of Carbon	Chemical Formula	State	Main Reservoir
Carbon Dioxide	CO_2	Gas	Atmosphere
Carbonic Acid	H_2CO_3	Liquid	Ocean
Bicarbonate Ion	HCO_3^-	Liquid(dissolvedion)	Ocean

TABLE 2.7: (continued)

Form of Carbon	Chemical Formula	State	Main Reservoir
Organic Compounds	*Examples:* Glucose, $C_6H_{12}O_6$ Methane, CH_4	Solid Gas	Biosphere Organic Sediments (Fossil Fuels)
Other Carbon Compounds	*Examples:* Calcium Carbonate, $CaCO_3$ Calcium Magnesium Carbonate, $CaMg(CO_3)_2$	Solid Solid	Sedimentary Rock, Shells Sedimentary Rock

KEY: C = Carbon, O = Oxygen, H = Hydrogen

Carbon in the Atmosphere

In the atmosphere, carbon exists primarily as carbon dioxide (CO_2). Carbon dioxide enters the atmosphere from several different sources, including those listed below. Most of the sources are also represented in **Figure 2.25,** and some are described in detail later in the lesson.

- Living organisms release carbon dioxide as a byproduct of cellular respiration.
- Carbon dioxide is given off when dead organisms and other organic materials decompose.
- Burning organic material, such as fossil fuels, releases carbon dioxide.
- When volcanoes erupt, they give off carbon dioxide that is stored in the mantle.
- Carbon dioxide is released when limestone is heated during the production of cement.
- Ocean water releases dissolved carbon dioxide into the atmosphere when water temperature rises.

A much smaller amount of carbon in the atmosphere is present as methane gas (CH_4). Methane is released into the atmosphere when dead organisms and other organic matter decay in the absence of oxygen. It is produced by landfills, the mining of fossil fuels, and some types of agriculture.

There are also several different ways that carbon leaves the atmosphere. Carbon dioxide is removed from the atmosphere when plants and other autotrophs take in carbon dioxide to make organic compounds during photosynthesis or chemosynthesis. Carbon dioxide is also removed when ocean water cools and dissolves more carbon dioxide from the air.

Because of human activities, there is more carbon dioxide in the atmosphere today than in the past hundreds of thousands of years. Burning fossil fuels and producing concrete has released great quantities of carbon dioxide into the atmosphere. Cutting forests and clearing land has also increased carbon dioxide into the atmosphere because these activities reduce the number of autotrophic organisms that use up carbon dioxide in photosynthesis. In addition, clearing often involves burning, which releases carbon dioxide that was previously stored in autotrophs.

Carbon in the Biosphere

Bicarbonate ions near the surface of the ocean may be taken up by photosynthetic algae and bacteria that live near the surface. These and other autotrophic organisms use bicarbonate ions or other forms of carbon to synthesize organic compounds. Carbon is essential for life because it is the main ingredient of every type of organic compound. Organic compounds make up the cells and tissues of all organisms and keep organisms alive and functioning. Carbon enters all ecosystems, both terrestrial and aquatic, through autotrophs such as plants or algae. Autotrophs use carbon dioxide from the air, or bicarbonate ions from the water, to make organic compounds such as glucose. Heterotrophs consume the organic molecules and pass the carbon through food chains and webs.

How does carbon cycle back to the atmosphere or ocean? All organisms release carbon dioxide as a byproduct of cellular respiration. **Cellular respiration** is the process by which cells oxidize glucose and produce carbon dioxide,

water, and energy. Decomposers also release carbon dioxide when they break down dead organisms and other organic waste.

In a balanced ecosystem, the amount of carbon used in photosynthesis and passed through the ecosystem is about the same as the amount given off in respiration and decomposition. This cycling of carbon between the atmosphere and organisms forms an organic pathway in the carbon cycle. Carbon can cycle quickly through this organic pathway, especially in aquatic ecosystems. In fact, during a given period of time, much more carbon is recycled through the organic pathway than through the geological pathway you will read about next.

The Nitrogen Cycle

Nitrogen is also one of the most abundant elements in living things. It's important for constructing both proteins and nucleic acids like DNA. The great irony of the nitrogen cycle is that nitrogen gas (N_2) comprises the majority of the air we breathe, and yet is not accessible to us or plants in the gaseous form (**Figure** 2.26). In fact, plants often suffer from nitrogen deficiency even through they are surrounded by plenty of nitrogen gas!

In order for plants to make use of nitrogen, it must be converted into compounds with other elements. This can be accomplished several different ways. First, Nitrogen gas can be converted to nitrate ($NO_3{}^-$) through lightning strikes. Alternatively, special nitrogen-fixing bacteria can also convert nitrogen gas into useful forms, a process called **nitrogen fixation.** These bacteria live in nodules on the roots of plants in the pea family. In aquatic environments, bacteria in the water can fix nitrogen gas into ammonium ($NH_4{}^+$), which can be used by aquatic plants as a source of nitrogen.

Nitrogen also is released to the environment through decaying organisms or decaying wastes. These wastes often take on the form of ammonium. Ammonium in the soil can be converted to nitrate by a two-step process completed by two different types of bacteria. In the form of nitrate, it can be used by plants through a process called **assimilation**.

The conversion of nitrate back into nitrogen gas happens through the work of denitrifying bacteria. These bacteria often live in swamps and lakes. The release of nitrogen gas would equal the amount of nitrogen gas taken into living things if human activities did not influence the nitrogen cycle. These human activities include the burning of fossil fuels, which releases nitrogen oxide gasses into the atmosphere, leading to problems like acid rain.

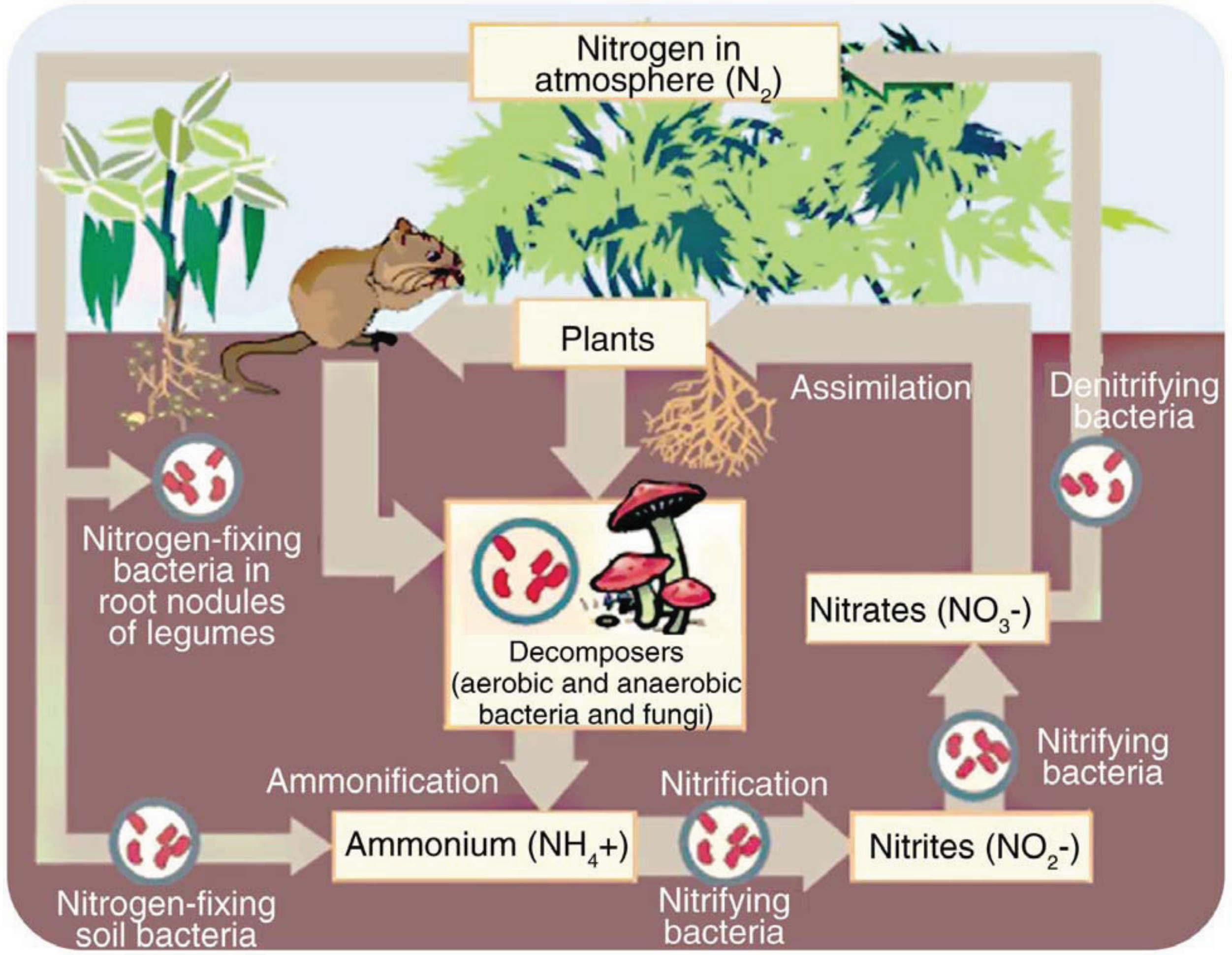


FIGURE 2.26
The nitrogen cycle includes assimilation, or uptake of nitrogen by plants; nitrogen-fixing bacteria that make the nitrogen available to plants in the form of nitrates; decomposers that convert nitrogen in dead organisms into ammonium; nitrifying bacteria that convert ammonium to nitrates; and denitrifying bacteria that convert help convert nitrates to gaseous nitrogen.

The Oxygen Cycle

The **Oxygen cycle** is the biogeochemical

Reservoirs

By far the largest reservoir of Earth's oxygen is within the silicate and oxide minerals of the crust and mantle (99.5%). Only a small portion has been released as free oxygen to the biosphere (0.01%) and atmosphere (0.36%). The main source of atmospheric oxygen is photosynthesis, which produces sugars and oxygen from carbon dioxide and water.

Photosynthesizing organisms include the plant life of the land areas as well as the phytoplankton of the oceans.

The tiny marine cyanobacterium Prochlorococcus was discovered in 1986 and accounts for more than half of the photosynthesis of the open ocean.

An additional source of atmospheric oxygen comes from photolysis, whereby high energy ultraviolet radiation breaks down atmospheric water and nitrous oxide into component atoms. The free H and N atoms escape into space leaving O_2 in the atmosphere:

$2H_2O$ + energy $\rightarrow$ 4H + O_2 $2N_2O$ + energy $\rightarrow$ 4N + O_2

The main way oxygen is lost from the atmosphere is via respiration and decay, mechanisms in which animal life and bacteria consume oxygen and release carbon dioxide.

Because lithospheric minerals are oxidised in oxygen, chemical weathering of exposed rocks also consumes oxygen. An example of surface weathering chemistry is formation of iron-oxides (rust).

Oxygen is also cycled between the biosphere and lithosphere. Marine organisms in the biosphere create calcium carbonate shell material ($CaCO_3$) that is rich in oxygen. When the organism dies its shell is deposited on the shallow sea floor and buried over time to create the limestone rock of the lithosphere. Weathering processes initiated by organisms can also free oxygen from the lithosphere. Plants and animals extract nutrient minerals from rocks and release oxygen in the process.

Ozone

The presence of atmospheric oxygen has led to the formation of ozone (O_3) and the ozone layer within the stratosphere. The ozone layer is extremely important to modern life as it absorbs harmful ultraviolet radiation:

O_2 + uv energy $\rightarrow$ 2O O + O_2 $\rightarrow$ O_3

The Phosphorus Cycle

The **phosphorus cycle** is the biogeochemical cycle that describes the movement of phosphorus through the lithosphere,hydrosphere, and biosphere. Unlike many other biogeochemical cycles, the atmosphere does not play a significant role in the movement of phosphorus, because phosphorus and phosphorus-based compounds are usually solids at the typical ranges of temperature and pressure found on Earth.

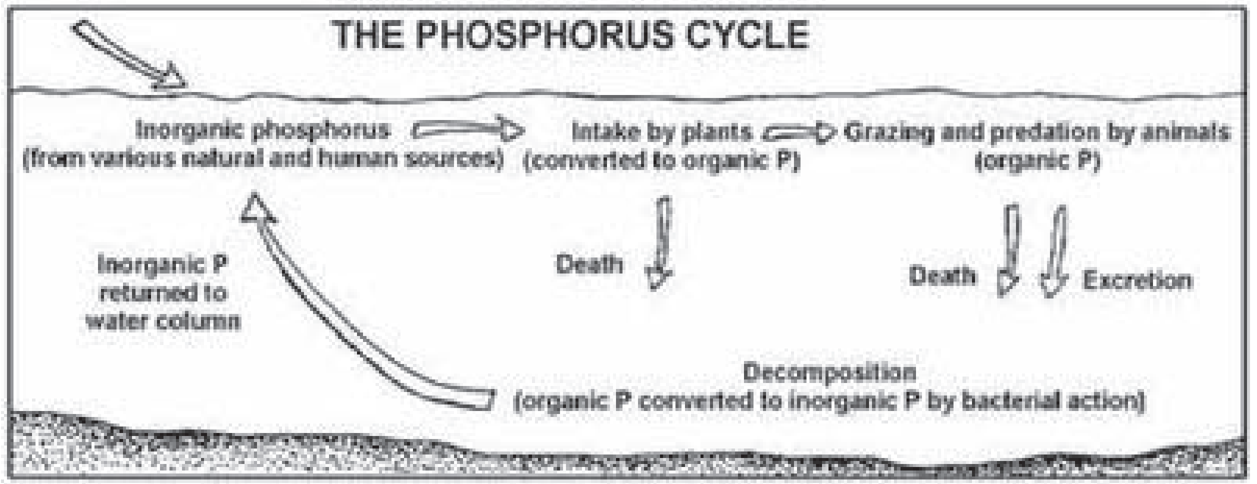


FIGURE 2.27

Phosphorus in the environment

Ecological function

Phosphorus is an essential nutrient for plants and animals in the form of ions. Phosphorus is a limiting nutrient for aquatic organisms. Phosphorus forms parts of important life sustaining molecules but are very common in the biosphere. Phosphorus does not enter the atmosphere, remaining mostly on land and in rock and soil minerals. Eighty percent of the phosphorus is used to make fertilizers and a type of phosphorus such as dilute phosphoric acid is used in soft drinks. Phosphates may be effective in such ways but also causes pollution issues in lakes and streams. Over enrichment of phosphate can lead to algae bloom, because of the excess nutrients. This causes more algae to grow, bacteria consumes the algae and causes more bacteria to grow in large amounts. They use all the oxygen in the water during cellular respiration, causing many fish to die.

Initially, phosphate weathers from rocks. The small losses in a terrestrial system caused by leaching through the action of rain are balanced in the gains from weathering rocks. In soil, phosphate is absorbed on clay surfaces and organic matter particles and becomes incorporated (immobilized). Plants dissolve ionized forms of phosphate. Herbivores obtain phosphorus by eating plants, and carnivores by eating herbivores. Herbivores and carnivores excrete phosphorus as a waste product in urine and feces. Phosphorus is released back to the soil when plants or animal matter decomposes and the cycle repeats.

Biological Function

The primary biological importance of phosphates is as a component of nucleotides, which serve as energy storage within cells (ATP) or when linked together, form the nucleic acids DNA and RNA.The double helix of our DNA is only possible because of the phosphate ester bridge that binds the helix. Besides making biomolecules phosphorus is also found in bones, whose strength is derived from calcium phosphate in enamel of mammalian teeth; exoskeleton of insects and phospholipids(found in all biological membranes). It also functions as buffering agent in maintaining acid base homeostasis in the human body.

Process of the cycle

Phosphates move quickly through plants and animals; however, the processes that move them through the soil or ocean are very slow, making the phosphorus cycle overall one of the slowest biogeochemical cycles.

Unlike other cycles of matter compounds, phosphorus cannot usually be found in air as a gas, it only occurs under highly reducing conditions as the gas Phosphine PH3. This is because at normal temperature and circumstances, it is a solid in the form of red and white phosphorus. It usually cycles through water, soil and sediments. Phosphorus is typically the limiting nutrient found in streams, lakes and fresh water environments. As rocks and sediments gradually wear down, phosphate is released. In the atmosphere phosphorus is mainly small dust particles.

Human interference

Nutrients are important to the growth and survival of living organisms, and hence, are essential for development and maintenance of healthy ecosystems. However, excessive amounts of nutrients, particularly phosphorus and nitrogen, are detrimental to aquatic ecosystems. Natural eutrophication is a process by which lakes gradually age and become more productive and may take thousands of years to progress. Cultural or anthropogenic **eutrophication**, however, is water pollution caused by excessive plant nutrients, which results in excessive growth in algae population. Surface and subsurface runoff and erosion from high-P soils may be major contributing factors to fresh water eutrophication. The processes controlling soil P release to surface runoff and to subsurface flow are a complex interaction between the type of P input, soil type and management, and transport processes depending on hydrological conditions.

Human interference in the phosphorus cycle occurs by overuse or careless use of phosphorus fertilizers. This results

in increased amounts of phosphorus as pollutants in bodies of water resulting in eutrophication. Eutrophication devastates water ecosystems.

Lesson Summary

- During the water cycle, water enters the atmosphere through evaporation, and water returns to land through precipitation.
- During the carbon cycle, animals add carbon dioxide to the atmosphere through respiration and plants remove carbon dioxide through photosynthesis.
- During the nitrogen cycle, gaseous nitrogen is converted into water-soluble forms that can be used by plants, while denitrifying bacteria convert nitrate back to gaseous nitrogen.
- During the oxygen cycle, photosynthesis drives this cycle and the protective ozone layer is a product of the oxygen cycle.
- During the phosphorus cycle, rocks weather to release phosphorus which is absorbed by plants that are eaten by animals and then decomposers put is back into rocks

Review Questions

1. What human activities have thrown the carbon cycle off balance?
2. What biological process "fixes" carbon, removing it from the atmosphere?
3. What is the significance of nitrogen-fixing bacteria?
4. What is the term for the remains of organisms that are burned for energy?
5. How does water in the atmosphere return to the ground?
6. What biological process releases carbon back into the atmosphere?
7. What are some examples of fossil fuels?
8. Why is carbon dioxide referred to as a "greenhouse gas"?
9. What must happen for plants to use nitrogen in the atmosphere?
10. What is the significance of denitrifying bacteria?

Points to Consider

- Do ecosystems change over time? Why or why not?
- Can you think of an example of a ecosystem changing over time?

2.8 Ecosystem Change

Lesson Objectives

- Explain the process of ecological succession.
- Distinguish between secondary and primary succession.
- Describe a climax community.

Check Your Understanding

- What is a biome?
- What is the most abundant element in living things?
- How do humans obtain nitrogen?

Introduction

When you see an established forest, it's easy to picture that the forest has been there forever. This is not the case, however. Ecosystems are dynamic and change over time. That forest may lie on land that was once covered by an ocean millions of years ago. Or the forest may have been cut down at one point for agricultural use, then abandoned and allowed to re-establish itself over time. During the ice ages, glaciers once covered areas that are tropical rainforests today. Due to both natural forces and the influence of humans, ecosystems are constantly changing.

Primary Succession

If conditions of an ecosystem change drastically due to natural forces or human impact, the community of plants and animals that live there may be destroyed or be forced to relocate. Over time a new community will be established, and then that community may be replaced by another. You may see several changes in the plant and animal composition of the community over time. **Ecological succession** is the continual replacement of one community by another that occurs after some disturbance of the ecosystem.

But ecological succession must also occur on new land, in an area that has not supported life before. **Primary succession** (**Figure**2.28) is the type of ecological succession that happens in barren lands, such as those created by lava flow or retreating glaciers. Since the land that results from these processes is often completely new land, part of the primary succession process is soil formation.

Primary succession always starts with the establishment of a **pioneer species**, a species that first inhabits the disturbed area. In the case of barren rock, the pioneer species is lichen, a symbiotic relationship between a fungus and an algae or cyanobacteria. The fungus is able to absorb minerals and nutrients from the rock, and the algae or cyanobacteria is provides carbohydrates from photosynthesis. Since the lichen can photosynthesize and do not rely on soil, lichen can live in desolate environments. As the lichen grows, it breaks down the rock, which is the first step of soil formation.

FIGURE 2.28
Primary succession on a rock often begins with the growth of lichen.

The pioneer species is soon replaced by a series of other communities. Mosses and grasses will be able to grow in the newly created soil. During early succession, plant species like grasses that grow and reproduce quickly will be favored and take over the landscape. Over time, these plants improve the soil further and a few shrubs can begin to grow. Gradually the shrubs are then replaced by trees. Since trees are more successful competing for resources than shrubs and grasses, a forest will be the end result of primary succession if the climate supports that type of biome.

Secondary Succession

Sometimes ecological succession occurs in places where there is already soil, and that has previously supported life. **Secondary succession** is the type of ecological succession that happens after something destroys the community, but yet soil remains in the area. One event that can lead to secondary succession is the abandonment of a field that was once used for agriculture (**Figure**2.29). In this case, the pioneer species would be the grasses that first appear. Gradually the field would return to the natural state and look like it used to look before the influence of man.

Another event that results in secondary succession is a forest fire (**Figure** 2.30 and 2.31). Although the area will look devastated at first, the seeds of new plants are underground and waiting for their chance to grow. Just like primary succession, the burned forest will go through a series of communities, starting with small grasses, then shrubs, and finally mature trees 2.32. An orderly process of succession will always occur, whether a community is destroyed by man or the forces of nature.

FIGURE 2.29
This land was once used for growing crops. Now that the field is abandoned, secondary succession has begun. Pioneer species, such as the grasses, first appear and then shrubs begin to grow

FIGURE 2.30
The early stages of succession after a forest fire are shown in these pictures. Taken four years after the fire, they show the charred remains of the original forest as well as the small grasses and shrubs that are beginning to grow back in the area.

FIGURE 2.31
The early stages of succession after a forest fire are shown in these pictures. Taken four years after the fire, they show the charred remains of the original forest as well as the small grasses and shrubs that are beginning to grow back in the area.

FIGURE 2.32
In 1988, a forest fire destroyed much of Yellowstone National Park. This photo, taken 17 years later, shows that the forest is gradually growing back. Small grasses first grew here and are now being replaced by small trees and shrubs. This is an example of the later stages of secondary succession.

Climax Communities

Climax communities (**Figure** 2.33) are the end result of ecological succession. In contrast with the series of changes that occur during ecological succession, the climax community is stable. The climax community will remain in equilibrium unless a disaster strikes and succession would have to start all over again.

Depending on the climate of the area, the composition of the climax community is different. In the tropics, the climax community might be a tropical rainforest. At the other extreme, in the northern parts of the world, the climax community might be a coniferous forest. The natural state of the biome defines the climax community.

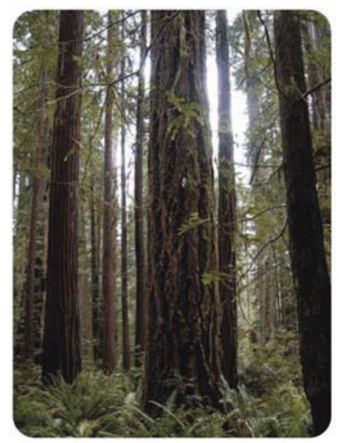


FIGURE 2.33
These ancient redwood trees are part of a climax community, the end result of a series of community replacements during succession.

Lesson Summary

- Ecological succession is the continual replacement of one community by another that occurs after some disturbance of the ecosystem.
- Primary succession occurs in disturbed areas that have no or little soil, while secondary succession occurs in disturbed areas that previously supported life.

- Climax communities are the end product of succession, when the ecosystem is again stable.

Review Questions

1. What is the term for a continuous replacement of one community by another following a disturbance?
2. What type of succession occurs in areas where there is no soil?
3. What type of succession occurs in areas where soil is present?
4. What is the term for the final stage of succession, when the community becomes stable?
5. Imagine a forest fire destroyed a forest. The forest will slowly re-establish itself, which is an example of what kind of succession?
6. A glacier slowly melts, leaving bare rock behind it. As life starts establishing itself on the newly available land, what kind of succession is this?
7. Does the climax community look the same in all parts of the world?

Points to Consider

- Think about what would happen if dangerous toxins were illegally dumped near a river?
- Discuss why it is important to seek alternative energy sources.
- Do we have an infinite supply of fossil fuels, or can we run out some day?

Vocabulary Students will need to Learn:

Predator-prey

symbiosis

competition

ecosystem

carbon cycle

nitrogen cycle

oxygen cycle

phosphorus cycle

population

diversity

energy pyramid

consumers

producers

limiting factor

competition

decomposers

food chain

biotic

abiotic

community

Primary succession

Secondary succession

Chapter 3 Chemistry of Life - BioChemistry - edited

Chapter Outline

3.1 Components of Matter

Lesson Objectives

- Describe elements and compounds, and explain how mixtures differ from compounds.
- Define energy, and describe how energy can be changed from one form to another.
- Identify three states of matter, and explain how they differ.

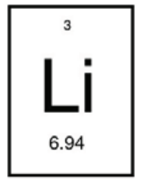
Introduction

Living things are made of **matter.** In fact, matter is the "stuff" of which all things are made. Anything that occupies space and has mass is known as matter. Matter, in turn, consists of chemical substances.

Chemical Substances

A chemical substance is a material that has a definite chemical composition. It is also homogeneous, so the same chemical composition is found uniformly throughout the substance. A chemical substance may be an element or a chemical compound.

Elements



An **element** is a pure substance that cannot be broken down into different types of substances. Examples of elements include carbon, oxygen, hydrogen, and iron. The most abondant elements in cells are carbon, hydrogen, nitrogen, oxygen, phosphorous, and sulfur. Each element is made up of just one type of atom. An **atom** is the smallest particle of an element that still characterizes the element. As shown in **Figure** 3.1, at the center of an atom is a nucleus. The **nucleus** contains positively charged particles called protons and electrically neutral particles called neutrons. Surrounding the nucleus is a much larger **electron cloud** consisting of negatively charged electrons. **Valence electrons** are the electrons in the outermost shell (energy level) of an atom. An atom is electrically neutral if it has the same number of protons as electrons. If an atom has an electrical charge it is called an **ion**. There are two different ion. an **Anion** is an atom that has a negative charge, so it has gained electrons. A **Cation** is an ion with a positive charge, so it has lost electrons. **Isotope** is an element that is the same, has the same number of protons, but has a different number of neutrons. An example of an isotope is Carbon 14 and Carbon 15. Each element has atoms with a characteristic number of protons. For example, all carbon atoms have six protons, and all oxygen atoms have eight protons.

There are almost 120 known elements (**Figure** 3.2). The majority of known elements are classified as metals. Metals are elements that are lustrous, or shiny. They are also good conductors of electricity and heat. Examples of metals include iron, gold, and copper. Fewer than 20 elements are classified as nonmetals. Nonmetals lack the properties of metals. Examples of nonmetals include oxygen, hydrogen, and sulfur. Certain other elements have properties of both metals and nonmetals. They are known as metalloids. Examples of metalloids include silicon and boron.

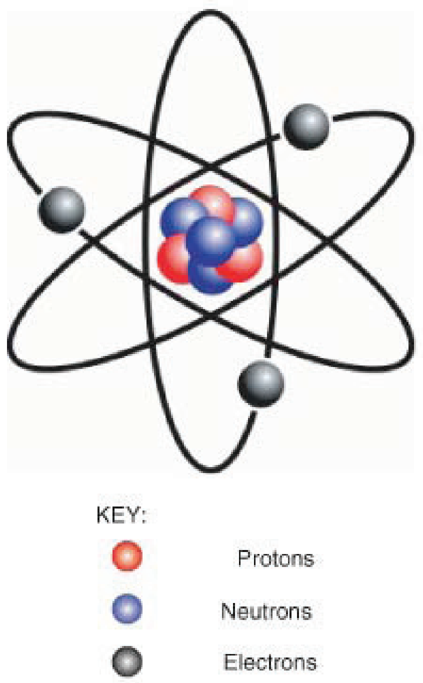


FIGURE 3.1
Model of an Atom. The protons and neutrons of this atom make up its nucleus. Electrons surround the nucleus. KEY: Red = protons, Blue = neutrons, Black = electrons.

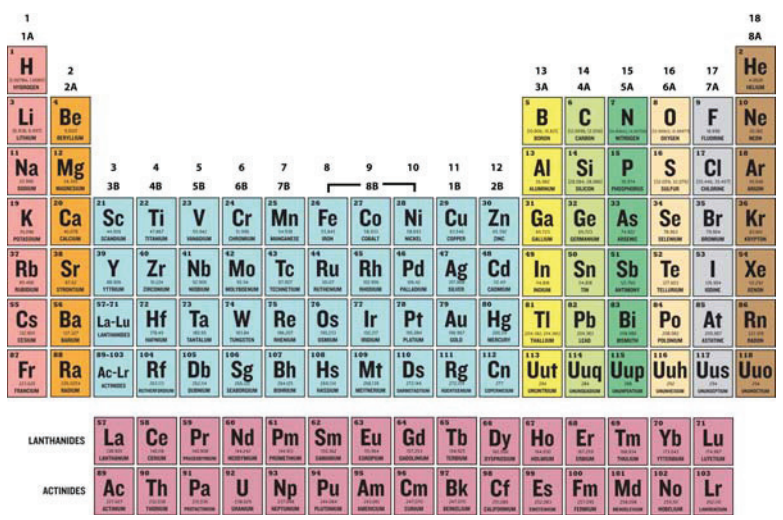


FIGURE 3.2
The Periodic Table.

Chemical Compounds

A **chemical compound** is a new substance that forms when atoms of two or more elements react with one another. A chemical reaction is a process that changes some chemical substances into other chemical substances. A compound that results from a chemical reaction always has a unique and fixed chemical composition. The substances in the compound can be separated from one another only by another chemical reaction. This is covered further in the *Chemical Reactions* lesson.

The atoms of a compound are held together by **chemical bonds.** Chemical bonds form to stablize an atom. Atoms become stable when there outer energy shell (level) is full. There are different types of chemical bonds, and they vary in how strongly they hold together the atoms of a compound. Two of the strongest types of bonds are covalent and ionic bonds. **Covalent bonds** form between atoms when they share electrons in order to become stable, fill their outer shell. Covalent bonds are similar to a couple holding hands. Their fingers share a space and they become stable. **Ionic bonds**, in contrast, form between atoms that are electronically charged. Opposites attract, so a cation will attract to an anion creating an ionic bond. An ionic bond is formed when two guys go to a party. They hangout until they find someone of the opposite gender that is more attractive.

Energy is release when bonds are formed and Energy is required when bonds are released. For Example, when a guy is sitting next to a girl at the movies and is looking for that perfect moment to hold her hand there is controlled energy. When the bond is made between the boys hand and the girls, the sigh of relief is that release of energy. As opposed to breaking of bonds. A couple doesn't break their bond until after a big fight. A big fight requires a lot of energy.

An example of a chemical compound is water. A water molecule forms when oxygen (O) and hydrogen (H) atoms react and are held together by covalent bonds. Like other compounds, water always has the same chemical composition: a 2:1 ratio of hydrogen atoms to oxygen atoms. This is expressed in the chemical formula H_2O. A model of a water molecule is shown in **Figure** 3.3.

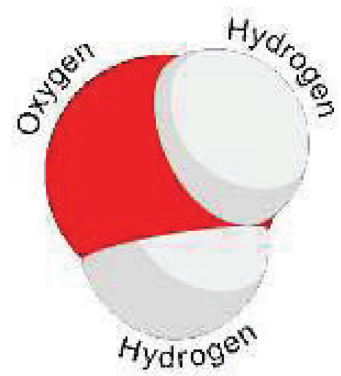


FIGURE 3.3
Model of a water molecule, showing the arrangement of hydrogen and oxygen atoms

Compounds that contain mainly the elements carbon and hydrogen are called **organic compounds**. This is because they are found mainly in living organisms. Most organic compounds are held together by covalent bonds. An example of an organic compound is glucose ($C_6H_{12}O_6$), which is shown in **Figure** 3.4. Glucose is a simple sugar that living cells use for energy. All other compounds are called inorganic compounds. Water is an example of an inorganic compound. You will read more about organic compounds in Lesson 2.2.

Mixtures vs. Compounds

Like a chemical compound, a **mixture** consists of more than one chemical substance. Unlike a compound, a mixture does not have a fixed chemical composition. The substances in a mixture can be combined in any proportions. A mixture also does not involve a chemical reaction. Therefore, the substances in a mixture are not changed into unique new substances, and they can be separated from each other without a chemical reaction.

The following examples illustrate these differences between mixtures and compounds. Both examples involve the same two elements: the metal iron (Fe) and the nonmetal sulfur (S).

- When iron filings and sulfur powder are mixed together in any ratio, they form a mixture. No chemical reaction occurs, and both elements retain their individual properties. A magnet can be used to mechanically separate the two elements by attracting the iron filings out of the mixture and leaving the sulfur behind.

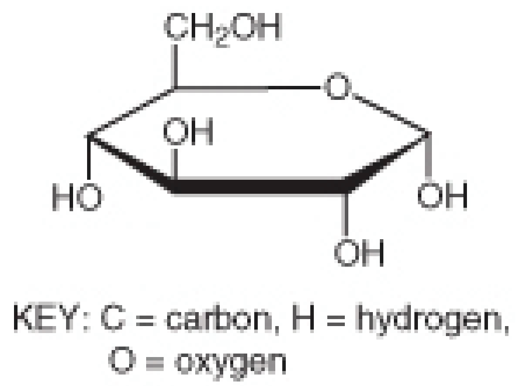


FIGURE 3.4
Glucose Molecule. This model represents a molecule of glucose, an organic compound composed of carbon, hydrogen, and oxygen. The chemical formula for glucose is CHO. This means that each molecule of glucose contains six carbon atoms, twelve hydrogen atoms, and six oxygen atoms. NOTE: Each unlabeled point where lines intersect represents another carbon atom. Some of these carbons and the oxygen atom are bonded to another hydrogen atom, not shown here.

- When iron and sulfur are mixed together in a certain ratio and heated, a chemical reaction occurs. This results in the formation of a unique new compound, called iron sulfide (FeS). A magnet cannot be used to mechanically separate the iron from the iron sulfide because metallic iron does not exist in the compound. Instead, another chemical reaction is required to separate the iron and sulfur.

Matter and Energy

Energy is a property of matter that is defined as the ability to do work. The concept of energy is useful for explaining and predicting most natural phenomena, and it is foundational for an understanding of biology. All living organisms need energy to grow and reproduce. However, energy can never be created or destroyed. It is always conserved. This is called the law of conservation of energy. Therefore, organisms cannot create the energy they need. Instead, they must obtain energy from the environment. Organisms also cannot destroy or use up the energy they obtain. They can only change it from one form to another.

Forms of Energy

Energy can take several different forms. Common forms of energy include light, chemical, and heat energy. Other common forms are kinetic and potential energy.

How Organisms Change Energy

In organisms, energy is always changing from one form to another. For example, plants obtain light energy from sunlight and change it to chemical energy in food molecules. Chemical energy is energy stored in bonds between atoms within food molecules. When other organisms eat and digest the food, they break the chemical bonds and release the chemical energy. Organisms do not use energy very efficiently. About 90 percent of the energy they obtain from food is converted to heat energy that is given off to the environment.

Kinetic and Potential Energy

Energy also constantly changes back and forth between kinetic and potential energy. **Kinetic energy** is the energy of movement. For example, a ball falling through the air has kinetic energy because it is moving (**Figure** 3.5). **Potential energy** is the energy stored in an object due to its position. A bouncing ball at the top of a bounce, just before it starts to fall, has potential energy. For that instant, the ball is not moving, but it has the potential to move because gravity is pulling on it. Once the ball starts to fall, the potential energy changes to kinetic energy. When the ball hits the ground, it gains potential energy from the impact. The potential energy changes to kinetic energy when the ball bounces back up into the air. As the ball gains height, it regains potential energy because of gravity.

FIGURE 3.5
Energy in a bouncing ball is transformed from potential energy to kinetic energy and then back to potential energy. This cycle of energy changes keeps repeating as long as the ball continues to bounce. The ball rises less on each successive bounce because some energy is used to resist air molecules.

Like the ball, every time you move you have kinetic energy — whether you jump or run or just blink your eyes. Can you think of situations in which you have potential energy? Obvious examples might include when you are standing on a diving board or at the top of a ski slope or bungee jump. What gives you potential energy in all of these situations? The answer is gravity.

Lesson Summary

- Matter consists of elements and compounds. A compound forms when elements combine in fixed proportions and undergo a chemical reaction. A mixture forms when substances combine in any proportions without a chemical reaction.
- Energy is a property of matter. It cannot be created or destroyed. Organisms obtain light energy from sunlight or chemical energy from food and change the energy into different forms, including heat energy.

Review Questions

1. Define element, and give an example of an element.
2. State how a compound differs from an element, and give an example of a compound.
3. What is energy?
4. What are three common states of matter?
5. Compare and contrast mixtures and compounds.
6. Explain what happens to molecules of matter when matter changes state from a liquid to a gas.

Points to Consider

Like all living things, you contain many organic compounds. For example, your brain is using the organic compound glucose as you read these words. Glucose provides brain cells with energy.

- What are some other organic compounds in your body?
- What roles do you think other organic compounds might play?
- Why are organic compounds able to carry out these roles?
- How do organic compounds differ from inorganic compounds?

3.2 Organic Compounds

Lesson Objectives

- Explain why **carbon** is essential to life on Earth.
- Describe the structure and function of carbohydrates.
- Describe the structure and function of lipids.
- Describe the structure and function of proteins.
- Describe the structure and function of nucleic acids.

Introduction

Organic compounds are chemical substances that make up organisms and carry out life processes. All organic compounds contain the elements carbon and hydrogen. Because carbon is the major element in organic compounds, it is essential to all known life on Earth. Without carbon, life as we know it could not exist.

The Significance of Carbon

Why is carbon so important to organisms? The answer lies with carbon's unique properties. Carbon has an exceptional ability to bind with a wide variety of other elements. Carbon atoms can form multiple stable bonds with other small atoms, including hydrogen, oxygen, and nitrogen. Carbon atoms can also form stable bonds with other carbon atoms. In fact, a carbon atom may form single, double, or even triple bonds with other carbon atoms. This allows carbon atoms to form a tremendous variety of very large and complex molecules.

Nearly 10 million carbon-containing organic compounds are known. Types of carbon compounds in organisms include carbohydrates, lipids, proteins, and nucleic acids. The elements found in each type are listed in Table 1. Elements other than carbon and hydrogen usually occur within organic compounds in smaller groups of elements called **functional groups**. When organic compounds react with other compounds, generally just the functional groups are involved. Therefore, functional groups generally determine the nature and functions of organic compounds.

TABLE 3.1: **Organic Compounds**

Type of Compound	Elements It Contains	Examples
Carbohydrates	Carbon, hydrogen, oxygen	Glucose, Starch, Glycogen
Lipids	Carbon, hydrogen, oxygen	Cholesterol, Triglycerides (fats) Phospholipids
Proteins	Carbon, hydrogen, oxygen, nitrogen, sulfur	Enzymes, Antibodies
Nucleic Acids	Carbon, hydrogen, oxygen, nitrogen, phosphorus	Deoxyribonucleic acid (DNA) Ribonucleic acid (RNA)

This table lists the four types of organic compounds, the elements they contain, and examples of each type of compound.

Carbohydrates

Carbohydrates are organic compounds that contain only carbon, hydrogen, and oxygen. They are the most common of the four major types of organic compounds. There are thousands of different carbohydrates, but they all consist of one or more smaller units called monosaccharides.

Monosaccharides and Disaccharides

The general formula for a **monosaccharide** is:

$(CH_2O)_n$,

where n can be any number greater than two. For example, if n is 6, then the formula can be written:

$C_6H_{12}O_6$.

This is the formula for the monosaccharide glucose. Another monosaccharide, fructose, has the same chemical formula as glucose, but the atoms are arranged differently. Molecules with the same chemical formula but with atoms in a different arrangement are called isomers. Compare the glucose and fructose molecules in **Figure** below. Can you identify their differences? The only differences are the positions of some of the atoms. These differences affect the properties of the two monosaccharides.

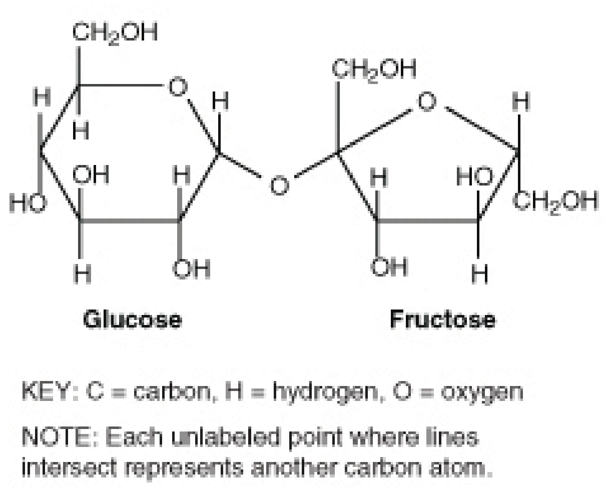


FIGURE 3.6
Sucrose Molecule. This sucrose molecule is a disaccharide. It is made up of two monosaccharides: glucose on the left and fructose on the right.

If two monosaccharides bond together, they form a carbohydrate called a **disaccharide**. An example of a disaccharide is sucrose (table sugar), which consists of the monosaccharides glucose and fructose (**Figure** above). Monosaccharides and disaccharides are also called **simple sugars**. They provide the major source of energy to living cells.

Polysaccharides

If more than two monosaccharides bond together, they form a carbohydrate called a **polysaccharide**. A polysaccharide may contain anywhere from a few monosaccharides to several thousand monosaccharides. Polysaccharides are also called **complex carbohydrates**. Their main functions are to store energy and form structural tissues. Examples of several polysaccharides and their roles are listed in Table 2.

TABLE 3.2: **Complex Carbohydrates**

Complex Carbohydrate	Function	Organism
Amylose	Stores energy	Plants
Glycogen	Stores energy	Animals
Cellulose	Forms cell walls	Plants
Chitin	Forms external skeleton	Some animals

These complex carbohydrates play important roles in living organisms.

Lipids

Lipids are organic compounds that contain mainly carbon, hydrogen, and oxygen. They include substances such as fats and oils. Lipid molecules consist of fatty acids, with or without additional molecules. **Fatty acids** are organic compounds that have the general formula $CH_3(CH_2)_nCOOH$, where n usually ranges from 2 to 28 and is always an even number.

Saturated and Unsaturated Fatty Acids

Fatty acids can be saturated or unsaturated. The term saturated refers to the placement of hydrogen atoms around the carbon atoms. In a **saturated fatty acid**, all the carbon atoms (other than the carbon in the -COOH group) are bonded to as many hydrogen atoms as possible (usually two hydrogens). Saturated fatty acids do not contain any other groups except -COOH. This is why they form straight chains, as shown in **Figure** below. Because of this structure, saturated fatty acids can be packed together very tightly. This allows organisms to store chemical energy very densely. The fatty tissues of animals contain mainly saturated fatty acids.

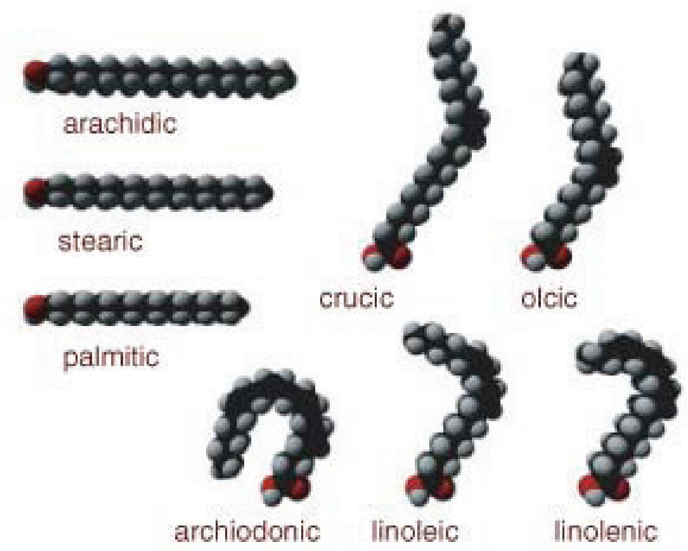


FIGURE 3.7

In an **unsaturated fatty acid**, some carbon atoms are not bonded to as many hydrogen atoms as possible. This is because they are bonded to one or more additional groups, including double and triple bonds between carbons. Wherever these other groups bind with carbon, they cause the chain to bend - they do not form straight chains (**Figure** above). This gives unsaturated fatty acids different properties than saturated fatty acids. For example, unsaturated fatty acids are liquids at room temperature whereas saturated fatty acids are solids. Unsaturated fatty acids are found mainly in plants, especially in fatty tissues such as nuts and seeds.

Unsaturated fatty acids occur naturally in the bent shapes shown in **Figure** above. However, unsaturated fatty acids can be artificially manufactured to have straight chains like saturated fatty acids. Called **trans fatty acids**, these synthetic lipids were commonly added to foods, until it was found that they increased the risk for certain health problems. Many food manufacturers no longer use trans fatty acids for this reason.

Types of Lipids

Lipids may consist of fatty acids alone or in combination with other compounds. Several types of lipids consist of fatty acids combined with a molecule of alcohol:

- **Triglycerides** are the main form of stored energy in animals. This type of lipid is commonly called fat. A triglyceride is shown in **Figure** below.
- **Phospholipids** are a major component of the membranes surrounding the cells of all organisms.
- **Steroids** (or sterols) have several functions. The sterol **cholesterol** is an important part of cell membranes and plays other vital roles in the body. Other steroids are male and female sex hormones (see *Reproductive System and Human Development*).

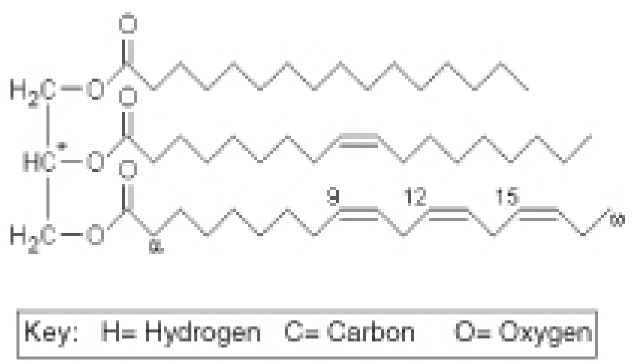


FIGURE 3.8

Lipids and Diet

Humans need lipids for many vital functions, such as storing energy and forming cell membranes. Lipids can also supply cells with energy. In fact, a gram of lipids supplies more than twice as much energy as a gram of carbohydrates or proteins. Lipids are necessary in the diet for most of these functions. Although the human body can manufacture most of the lipids it needs, there are others, called **essential fatty acids**, that must be consumed in food. Essential fatty acids include omega-3 and omega-6 fatty acids. Both of these fatty acids are needed for important biological processes, not just for energy.

Although some lipids in the diet are essential, excess dietary lipids can be harmful. Because lipids are very high in energy, eating too many may lead to unhealthy weight gain. A high-fat diet may also increase lipid levels in the blood. This, in turn, can increase the risk for health problems such as cardiovascular disease (see Circulatory and Respiratory Systems). The dietary lipids of most concern are saturated fatty acids, trans fats, and cholesterol. For example, cholesterol is the lipid mainly responsible for narrowing arteries and causing the disease atherosclerosis.

Proteins

Proteins are organic compounds that contain carbon, hydrogen, oxygen, nitrogen, and, in some cases, sulfur.

Proteins are made of smaller units called **amino acids**. There are 20 different common amino acids needed to make proteins. All amino acids have the same basic structure, which is shown in **Figure** below. Only the side chain (labeled R in the figure) differs from one amino acid to another. The variable side chain gives each amino acid unique properties. Proteins can differ from one another in the number and sequence (order) of amino acids. It is because of the side chains of the amino acids that proteins with different amino acid sequences have different shapes and different chemical properties.

Small proteins can contain just a few hundred amino acids. Yeast proteins average 466 amino acids. The largest known proteins are the titins, found in muscle, which are composed from almost 27,000 amino acids.

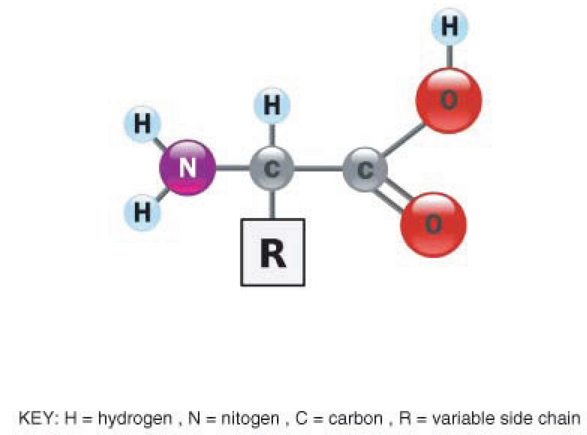


FIGURE 3.9

Protein Structure

Amino acids can bond together to form short chains called **peptides** or longer chains called **polypeptides** (**Figure** below). Polypeptides may have as few as 40 amino acids or as many as several thousand. A protein consists of one or more polypeptide chains. The sequence of amino acids in a protein's polypeptide chain(s) determines the overall structure and chemical properties of the protein. Primary protein structure is sequence of a chain of amino acids.

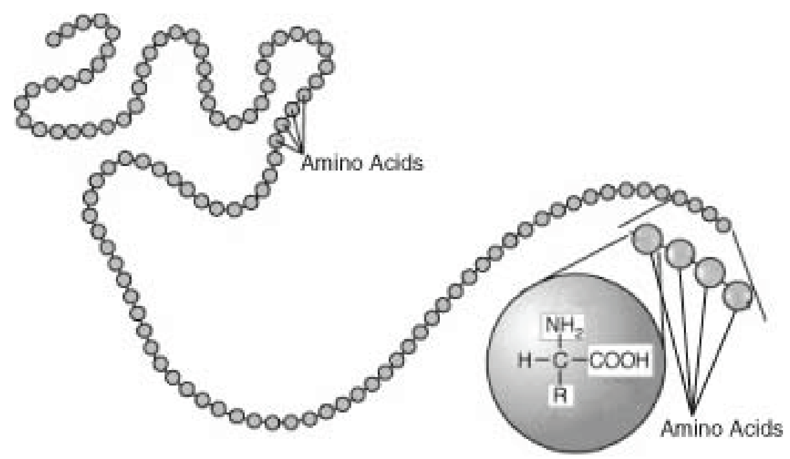


FIGURE 3.10

The amino acid sequence is the primary structure of a protein. As explained in **Figure** below, a protein may have up

to four levels of structure, from primary to quaternary. The complex structure of a protein allows it to carry out its biological functions.

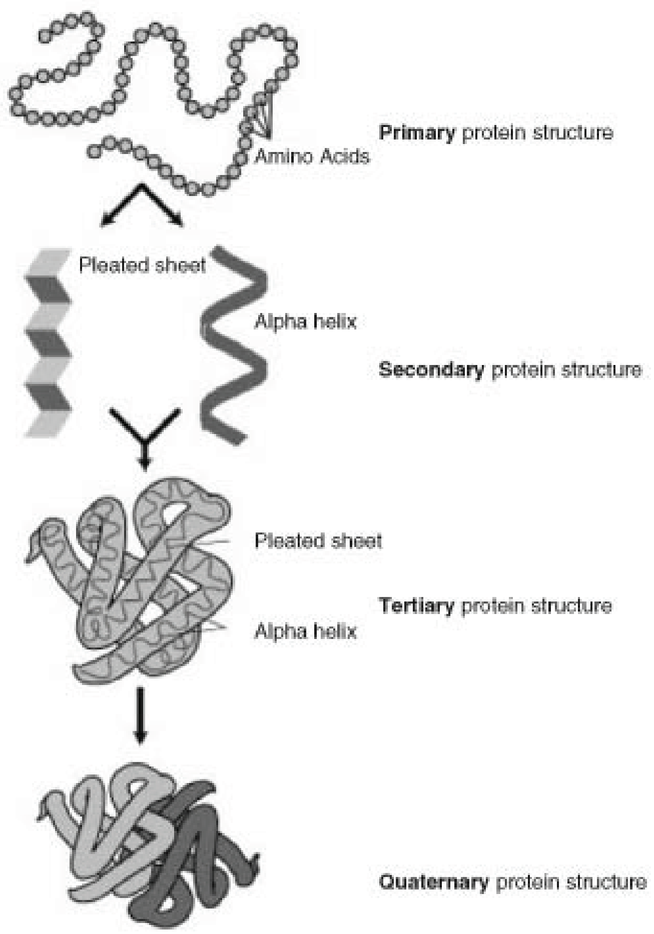


FIGURE 3.11

Functions of Proteins

Proteins are an essential part of all organisms. They play many roles in living things. Certain proteins provide a scaffolding that maintains the shape of cells. Proteins also make up the majority of muscle tissues. Many proteins are enzymes that speed up chemical reactions in cells (see the *Chemical Reactions* lesson). Other proteins are antibodies. They bond to foreign substances in the body and target them for destruction (see the Immune System and Disease chapter). Still other proteins help carry messages or materials in and out of cells or around the body. For example, the blood protein hemoglobin bonds with oxygen and carries it from the lungs to cells throughout the body.

One of the most important traits of proteins, allowing them to carry out these functions, is their ability to bond with other molecules. They can bond with other molecules very specifically and tightly. This ability, in turn, is due to the complex and highly specific structure of protein molecules.

Proteins and Diet

Proteins in the diet are necessary for life. Dietary proteins are broken down into their component amino acids when food is digested. Cells can then use the components to build new proteins. Humans are able to synthesize all but eight of the twenty common amino acids. These eight amino acids, called **essential amino acids**, must be consumed in foods. Like dietary carbohydrates and lipids, dietary proteins can also be broken down to provide cells with energy.

Nucleic Acids

Nucleic acids are organic compounds that contain carbon, hydrogen, oxygen, nitrogen, and phosphorus. They are made of smaller units called **nucleotides**. Nucleic acids are named for the nucleus of the cell, where some of them are found. Nucleic acids are found not only in all living cells but also in viruses. Types of nucleic acids include **deoxyribonucleic acid (DNA)** and **ribonucleic acid (RNA)**.

Structure of Nucleic Acids

A nucleic acid consists of one or two chains of nucleotides held together by chemical bonds. Each individual nucleotide unit consists of three parts:

- a base (containing nitrogen)
- a sugar (ribose in RNA, deoxyribose in DNA)
- a phosphate group (containing phosphorus)

The sugar of one nucleotide binds to the phosphate group of the next nucleotide. Alternating sugars and phosphate groups form the backbone of a nucleotide chain, as shown in **Figure** below. The bases, which are bound to the sugars, stick out at right angles from the backbone of the chain.

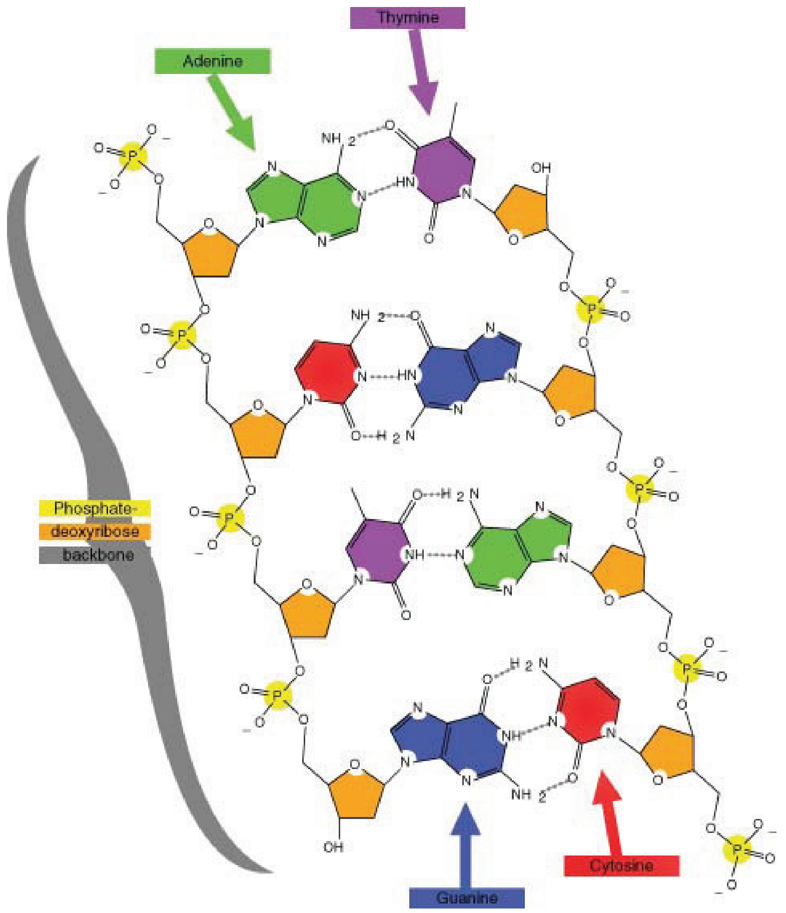


FIGURE 3.12

RNA consists of a single chain of nucleotides, and DNA consists of two chains of nucleotides. Bonds form between the bases on the two chains of DNA and hold the chains together (**Figure** above). There are four different types of bases in a nucleic acid molecule: cytosine, adenine, guanine, and either thymine (in DNA) or uracil (in RNA). Each type of base bonds with just one other type of base. Cytosine and guanine always bond together, and adenine and thymine (or uracil) always bond with one another. The pairs of bases that bond together are called **complementary bases**.

The binding of complementary bases allows DNA molecules to take their well-known shape, called a **double helix**. **Figure** below shows how two chains of nucleotides form a DNA double helix. A simplified double helix is illustrated in **Figure** below. It shows more clearly how the two chains are intertwined. The double helix shape forms naturally and is very strong. Being intertwined, the two chains are difficult to break apart. This is important given the fundamental role of DNA in all living organisms.

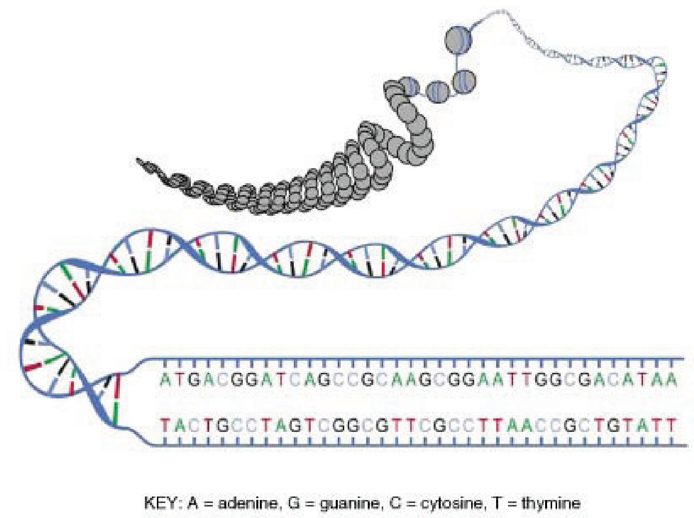


FIGURE 3.13

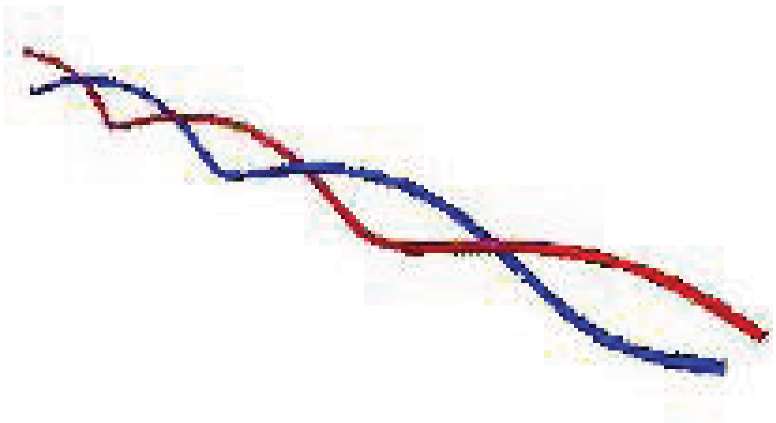


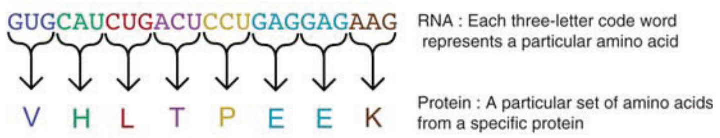
FIGURE 3.14

Role of Nucleic Acids

The order of bases in nucleic acids is highly significant. The bases are like the letters of a four-letter alphabet. These "letters" can be combined to form "words." Groups of three bases form words of the genetic code. Each code word stands for a different amino acid. A series of many code words spells out the sequence of amino acids in a protein (**Figure** below). In short, nucleic acids contain the information needed for cells to make proteins. This information is passed from a body cell to its daughter cells when the cell divides. It is also passed from parents to their offspring when organisms reproduce.

How RNA codes for Proteins

FIGURE 3.15



DNA and RNA have different functions relating to the genetic code and proteins. Like a set of blueprints, DNA contains the genetic instructions for the correct sequence of amino acids in proteins. RNA uses the information in DNA to assemble the amino acids and make the proteins. You will read more about the genetic code and the role of nucleic acids in protein synthesis in Chapter 8.

Lesson Summary

- Carbon's exceptional ability to form bonds with other elements and with itself allows it to form a huge number of large, complex molecules called organic molecules. These molecules make up organisms and carry out life processes.
- Carbohydrates are organic molecules that consist of carbon, hydrogen, and oxygen. They are made up of repeating units called saccharides. They provide cells with energy, store energy, and form structural tissues.
- Lipids are organic compounds that consist of carbon, hydrogen, and oxygen. They are made up of fatty acids and other compounds. They provide cells with energy, store energy, and help form cell membranes.
- Proteins are organic compounds that consist of carbon, hydrogen, oxygen, nitrogen, and, in some cases, sulfur. They are made up of repeating units called amino acids. They provide cells with energy, form tissues, speed up chemical reactions throughout the body, and perform many other cellular functions.
- Nucleic acids are organic compounds that consist of carbon, hydrogen, oxygen, nitrogen, and phosphorus. They are made up of repeating units called nucleotides. They contain genetic instructions for proteins, help synthesize proteins, and pass genetic instructions on to daughter cells and offspring.

Review Questions

1. State the function of monosaccharides, such as glucose and fructose.
2. Why do molecules of saturated and unsaturated fatty acids have different shapes?
3. What determines the primary structure of a protein?
4. Identify the three parts of a nucleotide.
5. What type of organic compound is represented by the formula $CH_3(CH_2)_4COOH$? How do you know?
6. Bases in nucleic acids are represented by the letters A, G, C, and T (or U). How are the bases in nucleic acids like the letters of an alphabet.
7. Why is carbon essential to all known life on Earth?
8. Compare and contrast simple sugars and complex carbohydrates.
9. State two functions of proteins, and explain how the functions depend on the ability of proteins to bind other molecules to them.

Points to Consider

Organisms are made up of thousands of very large, complex molecules called organic molecules. These molecules consist of repeating units of smaller molecules, such as amino acids or nucleotides.

- How do organic molecules form?
- How do smaller molecules join together to form larger molecules?
- What chemical processes are involved?

3.3 Water

Lesson Objectives

- Explain how the properties of water (e.g. cohesion, adhesion, heat capacity, solvent properties) contribute to maintainace of cells and living organisms.
- Identify the chemical structure of water, and explain how it relates to water's unique properties.
- Define solution, and describe water's role as a solvent.
- State how water is used to define acids and bases, and identify the pH ranges of acids and bases.
- Explain why water is essential for life processes.

Introduction

Water, like carbon, has a special role in biology because of its importance to organisms. Water is essential to all known forms of life. Water, H_2O, such a simple molecule, yet it is this simplicity that gives water its unique properties and explains why water is so vital for life.

Water, Water Everywhere

Water is a common chemical substance on Earth. The term water generally refers to its liquid state. Water is a liquid over a wide range of standard temperatures and pressures. However, water can also occur as a solid (ice) or gas (water vapor).

Where Is All the Water?

Of all the water on Earth, about two percent is stored underground in spaces between rocks. A fraction of a percent exists in the air as water vapor, clouds, or precipitation. Another fraction of a percent occurs in the bodies of plants and animals. So where is most of Earth's water? It's on the surface of the planet. In fact, water covers about 70 percent of Earth's surface. Of water on Earth's surface, 97 percent is salt water, mainly in the ocean. Only 3 percent is freshwater. Most of the freshwater is frozen in glaciers and polar ice caps. The remaining freshwater occurs in rivers, lakes, and other freshwater features.

Although clean freshwater is essential to human life, in many parts of the world it is in short supply. The amount of freshwater is not the issue. There is plenty of freshwater to go around, because water constantly recycles on Earth. However, freshwater is not necessarily located where it is needed, and clean freshwater is not always available.

Chemical Structure and Properties of Water

You are probably already familiar with many of water's properties (cohesion, adhesion, heat capacity, solvent properties). For example, you no doubt know that water is tasteless, odorless, and transparent. In small quantities, it is also colorless. However, when a large amount of water is observed, as in a lake or the ocean, it is actually light blue in color. These and other properties of water depend on its chemical structure.

The transparency of water is important for organisms that live in water. Because water is transparent, sunlight can pass through it. Sunlight is needed by water plants and other water organisms for photosynthesis.

Chemical Structure of Water

Each molecule of water consists of one atom of oxygen and two atoms of hydrogen, so it has the chemical formula H_2O. The arrangement of atoms in a water molecule, shown in **Figure** below, explains many of water's chemical properties. In each water molecule, the nucleus of the oxygen atom (with 8 positively charged protons) attracts electrons much more strongly than do the hydrogen nuclei (with only one positively charged proton). This results in a negative electrical charge near the oxygen atom (due to the "pull" of the negatively charged electrons toward the oxygen nucleus) and a positive electrical charge near the hydrogen atoms. A difference in electrical charge between different parts of a molecule is called **polarity**. A **polar molecule** is a molecule in which part of the molecule is positively charged and part of the molecule is negatively charged.

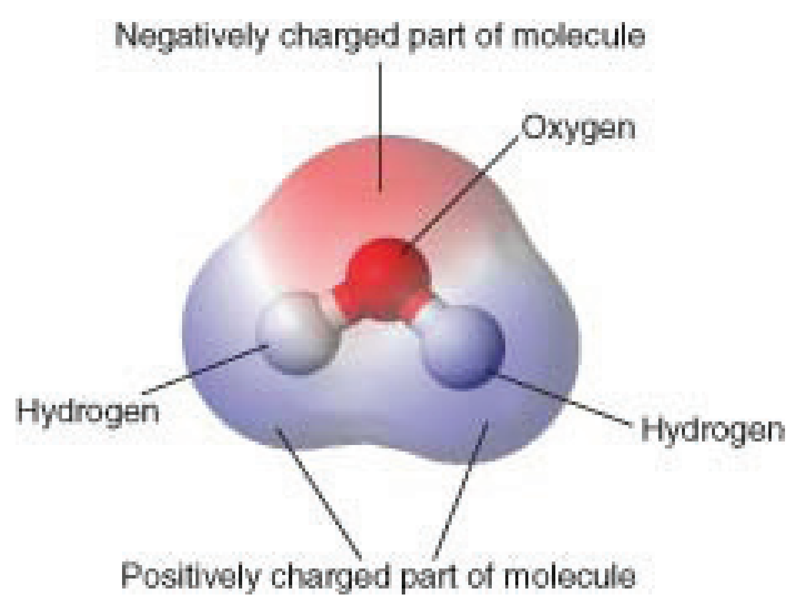


FIGURE 3.16

Opposite electrical charges attract one another. Therefore, the positive part of one water molecule is attracted to the negative parts of other water molecules. Because of this attraction, bonds form between hydrogen and oxygen atoms of adjacent water molecules, as demonstrated in **Figure** below. This type of bond always involves a hydrogen atom, so it is called a **hydrogen bond**. Hydrogen bonds are bonds between molecules, and they are not as strong as bonds within molecules. Nonetheless, they help hold water molecules together. Hydorgen bonds are like a crush on another girls boyfriend. You are attracted to the other guy, but you are attached to someone else.

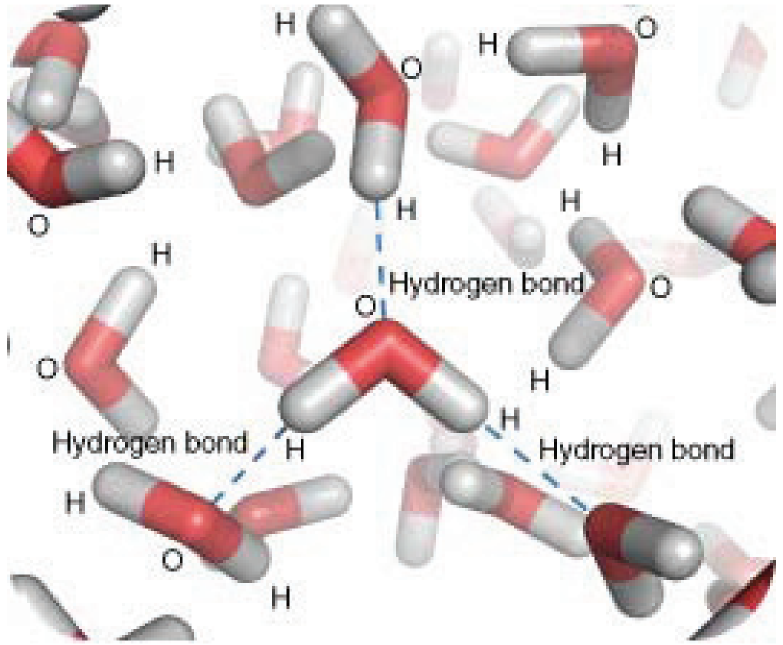


FIGURE 3.17

Hydrogen bonds can also form within a single large organic molecule. For example, hydrogen bonds that form between different parts of a protein molecule bend the molecule into a distinctive shape, which is important for the protein's functions. Hydrogen bonds also hold together the two nucleotide chains of a DNA molecule.

Sticky, Wet Water

Water has some unusual properties due to its hydrogen bonds. One property is the tendency for water molecules to stick together, **cohesion**. For example, if you drop a tiny amount of water onto a very smooth surface, the water molecules will stick together and form a droplet, rather than spread out over the surface. The same thing happens when water slowly drips from a leaky faucet. Adhesion is when water is attracted to other materials. The water doesn't fall from the faucet as individual water molecules but as droplets of water, this incorporates two properties of water cohesion and adhesion. Cohesion is the water sticking together to form the drop and adhesion is the water sticking to the faucet before it falls. The tendency of water to stick together in droplets is also illustrated by the dew drops in **Figure** below.

FIGURE 3.18

Hydrogen bonds also explain why water's boiling point (100° C) is higher than the boiling points of similar substances without hydrogen bonds. Because of water's relatively high boiling point, most water exists in a liquid state on Earth. Liquid water is needed by all living organisms. Therefore, the availability of liquid water enables life to survive over much of the planet.

Density of Ice and Water

The melting point of water is 0° C. Below this temperature, water is a solid (ice). Unlike most chemical substances, water in a solid state has a lower density than water in a liquid state. This is because water expands when it freezes. Again, hydrogen bonding is the reason. Hydrogen bonds cause water molecules to line up less efficiently in ice than in liquid water. As a result, water molecules are spaced farther apart in ice, giving ice a lower density than liquid water. A substance with lower density floats on a substance with higher density. This explains why ice floats on liquid water, whereas many other solids sink to the bottom of liquid water.

In a large body of water, such as a lake or the ocean, the water with the greatest density always sinks to the bottom. Water is most dense at about 4° C. As a result, the water at the bottom of a lake or the ocean usually has temperature of about 4° C. In climates with cold winters, this layer of 4° C water insulates the bottom of a lake from freezing temperatures. Lake organisms such as fish can survive the winter by staying in this cold, but unfrozen, water at the bottom of the lake.

Solutions

Water is one of the most common ingredients in solutions. A **solution** is a homogeneous mixture composed of two or more substances. In a solution, one substance is dissolved in another substance, forming a mixture that has the same proportion of substances throughout. The dissolved substance in a solution is called the **solute,** like salt in salt water . The substance in which is it dissolved is called the **solvent,** like the water in salt water. Water is known as the universal solvent, because is disolves most substances. In addition to a solid dissolved in a liquid, solutions can also form with solutes and solvents in other states of matter. Examples are given in **Table 1**.

TABLE 3.3: (continued)

Solvent	Gas	Liquid	Solid

TABLE 3.3: Solutions commonly form when a solid solute dissolves in a liquid solvent. However, solutions can form with solutes and solvents in any of the three major states of matter.

Solvent	Gas	Liquid	Solid
Gas	Oxygen and other gases in nitrogen (air)		
Liquid	Carbon dioxide in water (carbonated water)	Ethanol (an alcohol) in water	Sodium chloride in water (salt water)
Solid	Hydrogen in metals	Mercury in silver and other metals (dental fillings)	Iron in carbon (steel)

(*Source:* http://en.wikipedia.org/wiki/Solute, *License:* Creative Commons)

The ability of a solute to dissolve in a particular solvent is called **solubility**. Many chemical substances are soluble in water. In fact, so many substances are soluble in water that water is called the universal solvent. Water is a strongly polar solvent, and polar solvents are better at dissolving polar solutes. Many organic compounds and other important biochemicals are polar, so they dissolve well in water. On the other hand, strongly polar solvents like water cannot dissolve strongly nonpolar solutes like oil. Did you ever try to mix oil and water? Even after being well shaken, the two substances quickly separate into distinct layers.

Acids and Bases

Water is the solvent in solutions called acids and bases. To understand acids and bases, it is important to know more about pure water, in which nothing is dissolved. In pure water (such as distilled water), a tiny fraction of water molecules naturally breaks down, or dissociates, to form ions. An **ion** is an electrically charged atom or molecule. The dissociation of pure water into ions is represented by the chemical equation:

$2\ H_2O \rightarrow H_3O^+ + OH^-$.

The products of this reaction are a hydronium ion (H_3O^+) and a hydroxide ion (OH^-). The hydroxide ion is negatively charged. It forms when a water molecule donates, or gives up, a positively charged hydrogen ion. The hydronium ion, modeled in **Figure** below, is positively charged. It forms when a water molecule accepts a positively charged hydrogen ion (H^+).

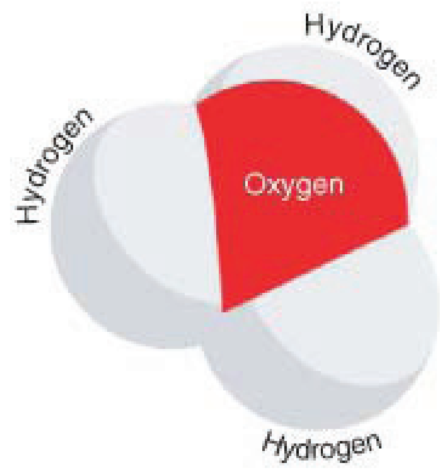


FIGURE 3.19

Acidity and pH

Acidity refers to the hydronium ion concentration of a solution. It is measured by **pH**. In pure water, the hydronium ion concentration is very low. Only about one in ten million water molecules naturally dissociates to form a hydronium ion in pure water. This gives water a pH of 7. The hydronium ions in pure water are also balanced by hydroxide ions, so pure water is neutral (neither an acid nor a base).

Because pure water is neutral, any other solution with the same hydronium ion concentration and pH is also considered to be neutral. If a solution has a higher concentration of hydronium ions and lower pH than pure water, it is called an **acid**. If a solution has a lower concentration of hydronium ions and higher pH than pure water, it is called a **base**. Several acids and bases and their pH values are identified on the pH scale, which ranges from 0 to 14, in **Figure** below.

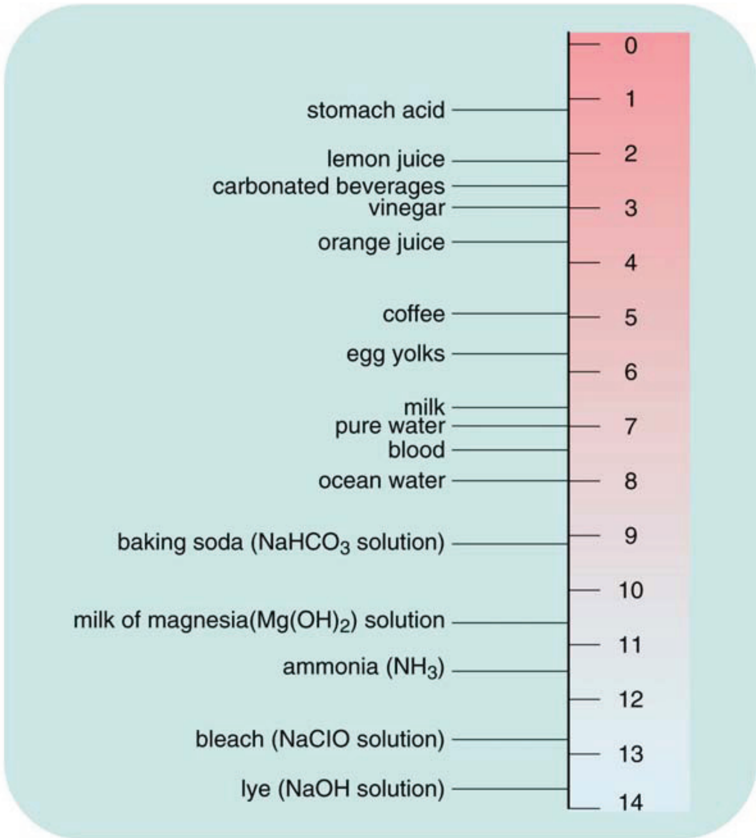


FIGURE 3.20

The pH scale is a negative logarithmic scale. Because the scale is negative, as the ion concentration increases, the pH value decreases. In other words, the more acidic the solution, the lower the pH value. Because the scale is logarithmic, each one-point change in pH reflects a ten-fold change in the hydronium ion concentration and acidity. For example, a solution with a pH of 6 is ten times as acidic as pure water with a pH of 7.

Acids

An acid can be defined as a hydrogen ion donor. The hydrogen ions bond with water molecules, leading to a higher concentration of hydronium ions than in pure water. For example, when hydrochloric acid (HCl) dissolves in pure water, it donates hydrogen ions (H^+) to water molecules, forming hydronium ions (H_3O^+) and chloride ions (Cl^-). This is represented by the chemical equation:

$HCl + H_2O \rightarrow Cl^- + H_3O^+$.

Strong acids can be harmful to organisms and damaging to materials. Acids have a sour taste and may sting or burn the skin. Testing solutions with litmus paper is an easy way to identify acids. Acids turn blue litmus paper red.

Bases

A base can be defined as a hydrogen ion acceptor. It accepts hydrogen ions from hydronium ions, leading to a lower concentration of hydronium ions than in pure water. For example, when the base ammonia (NH_3) dissolves in pure water, it accepts hydrogen ions (H^+) from hydronium ions (H_3O^+) to form ammonium ions (NH_4^+) and hydroxide ions (OH^-). This is represented by the chemical equation:

$NH_3 + H_2O \rightarrow NH_4^+ + OH^-$.

Like strong acids, strong bases can be harmful to organisms and damaging to materials. Bases have a bitter taste and feel slimy to the touch. They can also burn the skin. Bases, like acids, can be identified with litmus paper. Bases turn red litmus paper blue.

Neutralization

What do you think would happen if you mixed an acid and a base? If you think the acid and base would "cancel each other out," you are right. When an acid and base react, they form a neutral solution of water and a salt (a molecule composed of a positive and negative ion). This type of reaction is called a **neutralization** reaction. For example, when the base sodium hydroxide (NaOH) and hydrochloric acid (HCl) react, they form a neutral solution of water and the salt sodium chloride (NaCl). This reaction is represented by the chemical equation:

$NaOH + HCl \rightarrow NaCl + H_2O$.

In this reaction, hydroxide ions (OH^-) from the base combine with hydrogen ions (H^+) from the acid to form water. The other ions in the solution (Na^+) and (Cl^-) combine to form sodium chloride.

Acids and Bases in Organisms

Enzymes are needed to speed up biochemical reactions. Most enzymes require a specific range of pH in order to do their job. For example, the enzyme pepsin, which helps break down proteins in the human stomach, requires a very acidic environment in order to function. Strong acid is secreted into the stomach, allowing pepsin to work. Once the contents of the stomach enter the small intestine, where most digestion occurs, the acid must be neutralized. This is because enzymes that work in the small intestine need a basic environment. An organ near the small intestine, called the pancreas, secretes bicarbonate ions (HCO_3^-) into the small intestine to neutralize the stomach acid.

Bicarbonate ions play an important role in neutralizing acids throughout the body. Bicarbonate ions are especially important for protecting tissues of the central nervous system from changes in pH. The central nervous system includes the brain, which is the body's control center. If pH deviates too far from normal, the central nervous system cannot function properly. This can have a drastic effect on the rest of the body.

Water and Life

Humans are composed of about 70 percent water (not counting water in body fat). This water is crucial for normal functioning of the body. Water's ability to dissolve most biologically significant compounds—from inorganic salts to large organic molecules—makes it a vital solvent inside organisms and cells.

Water is an essential part of most metabolic processes within organisms. **Metabolism** is the sum total of all body reactions, including those that build up molecules (anabolic reactions) and those that break down molecules (catabolic reactions). In anabolic reactions, water is generally removed from small molecules in order to make larger molecules. In catabolic reactions, water is used to break bonds in larger molecules in order to make smaller molecules.

Water is central to two related, fundamental metabolic reactions in organisms: photosynthesis (*Photosynthesis* chapter) and respiration (*Cellular Respiration* chapter). All organisms depend directly or indirectly on these two reactions.

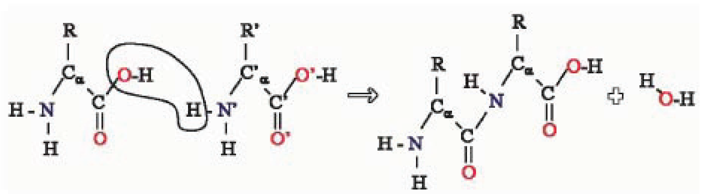
- In photosynthesis, cells use the energy in sunlight to change water and carbon dioxide into glucose and oxygen. This is an anabolic reaction, represented by the chemical equation:

$6\ CO_2 + 6\ H_2O + \text{energy} \rightarrow C_6H_{12}O_{6,} + 6\ O_2$.

- In cellular respiration, cells break down glucose in the presence of oxygen and release energy, water, and carbon dioxide. This is a catabolic reaction, represented by the chemical equation:

$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + \text{energy}$

Two other types of reactions that occur in organisms and involve water are dehydration and hydration reactions. A dehydration reaction occurs when molecules combine to form a single, larger molecule and also a molecule of water. (If some other small molecule is formed instead of water, the reaction is called by the more general term, condensation reaction.) It is a type of catabolic reaction. An example of a dehydration reaction is the formation of peptide bonds between amino acids in a polypeptide chain. When two amino acids bond together, a molecule of water is lost. This is shown in **Figure** below.



KEY : H = hydrogen, C = Carbon , O = Oxygen , N = nitrogen , R = side chain

FIGURE 3.21

A hydration reaction is the opposite of a dehydration reaction. A hydration reaction adds water to an organic molecule and breaks the large molecule into smaller molecules. Hydration reactions occur in an acidic water solution. An example of hydration reaction is the breaking of peptide bonds in polypeptides. A hydroxide ion (OH-) and a hydrogen ion (H+) (both from a water molecule) bond to the carbon atoms that formed the peptide bond. This breaks the peptide bond and results in two amino acids.

Water is essential for all of these important chemical reactions in organisms. As a result, virtually all life processes depend on water. Clearly, without water, life as we know it could not exist.

Lesson Summary

- Most of Earth's water is salt water located on the planet's surface. Water is constantly recycled through the water cycle.
- Water molecules are polar, so they form hydrogen bonds. This gives water unique properties, such as a relatively high boiling point.
- A solution is a homogeneous mixture in which a solute dissolves in a solvent. Water is a very common solvent, especially in organisms.
- The ion concentration of neutral, pure water gives water a pH of 7 and sets the standard for defining acids and bases. Acids have a pH lower than 7, and bases have a pH higher than 7.
- Water is essential for most life processes, including photosynthesis, cellular respiration, and other important chemical reactions that occur in organisms.

Review Questions

1. Where is most of Earth's water?
2. What is polarity, and why is water polar?
3. Define solution, and give an example of a solution.
4. What is the pH of a neutral solution? Why?

5. Draw a circle diagram to represent the water cycle. Identify the states of water and the processes in which water changes state throughout the cycle.
6. What type of reaction is represented by the chemical equation below? Defend your answer. $KOH + HCl \rightarrow KCl + H_2O$
7. Explain how hydrogen bonds cause molecules of liquid water to stick together.
8. Summarize how metabolism in organisms depends on water.

Points to Consider

Most life processes take place within cells. You probably know that cells are the microscopic building blocks of organisms.

- What do you think you would see if you could look inside a cell?
- What structures might you see?
- What processes might you observe?

3.4 Chemical Reactions

Lesson Objectives

- Describe what happens in a chemical reaction, and identify types of chemical reactions.
- Explain the role of energy in chemical reactions, and define activation energy.
- State factors that affect the rate of chemical reactions.
- Explain the importance of enzymes in organisms, and describe how enzymes work.

Introduction

A chemical compound may be very different from the substances that combine to form it. For example, the element chlorine (Cl) is a poisonous gas, but when it combines with sodium (Na) to form sodium chloride (NaCl), it is no longer toxic. You may even eat it on your food. Sodium chloride is just table salt. What process changes a toxic chemical like chlorine into a much different substance like table salt?

What are Chemical Reactions?

A **chemical reaction** is a process that changes some chemical substances into other chemical substances. The substances that start a chemical reaction are called **reactants**. The substances that form as a result of a chemical reaction are called **products**. During the reaction, the reactants are used up to create the products. For example, when methane burns in oxygen, it releases carbon dioxide and water. In this reaction, the reactants are methane (CH_4) and oxygen (O_2), and the products are carbon dioxide (CO_2) and water (H_2O).

Chemical Equations

A chemical reaction can be represented by a chemical equation. Using the same example, the burning of methane gas can be represented by the equation:

$$CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O.$$

The arrow in a chemical equation separates the reactants from the products and shows the direction in which the reaction occurs. If the reaction could also occur in the opposite direction, then two arrows, one pointing in each direction, would be used. On each side of the arrow, a mixture of chemicals is indicated by the chemical symbols joined by a plus sign (+). The numbers preceding some of the chemical symbols (such as 2 O_2) indicate how many molecules of the chemicals are involved in the reaction. (If there is no number in front of a chemical symbol, it means that just one molecule is involved.)

In a chemical reaction, the quantity of each element does not change. There is the same amount of each element at the end of the reaction as there was at the beginning. This is reflected in the chemical equation for the reaction. The equation should be balanced. In a balanced equation, the same number of atoms of a given element appear on each side of the arrow. For example, in the equation above, there are four hydrogen atoms on each side of the arrow.

Activation Energy

All reactions need energy to get started. This energy is called **activation energy**. Activation energy is like the push you need to start moving down a slide. The push gives you enough energy to start moving. Once you start, you keep moving without being pushed again. The concept of activation energy is illustrated in **Figure** 3.23.

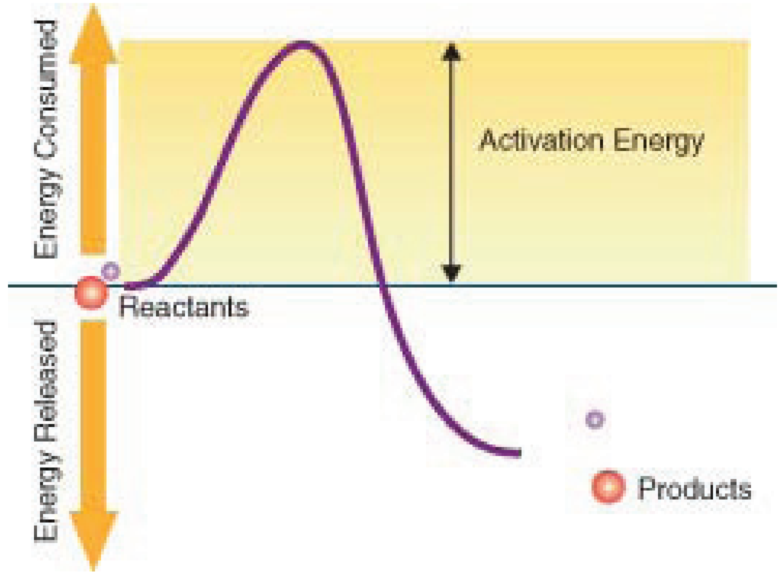


FIGURE 3.22

Why do reactions need energy to get started? In order for reactions to occur, three things must happen, and they all require energy:

- Reactant molecules must collide. To collide, they must move, so they need kinetic energy.
- Unless reactant molecules are positioned correctly, intermolecular forces may push them apart. To overcome these forces and move together requires more energy.
- If reactant molecules collide and move together, there must be enough energy left for them to react.

Rates of Chemical Reactions

The rates at which chemical reactions take place in organisms are very important. Chemical reactions in organisms are involved in processes ranging from the contraction of muscles to the digestion of food. For example, when you wave goodbye, it requires repeated contractions of muscles in your arm over a period of a couple of seconds. A huge number of reactions must take place in that time, so each reaction cannot take longer than a few milliseconds. If the reactions took much longer, you might not finish waving until sometime next year.

Factors that help reactant molecules collide and react speed up chemical reactions. These factors include the concentration of reactants and the temperature at which the reactions occur.

- Reactions are usually faster at higher concentrations of reactants. The more reactant molecules there are in a given space, the more likely they are to collide and react.
- Reactions are usually faster at higher temperatures. Reactant molecules at higher temperatures have more energy to move, collide, and react.

Enzymes and Biochemical Reactions

Most chemical reactions within organisms would be impossible under the conditions in cells. For example, the body temperature of most organisms is too low for reactions to occur quickly enough to carry out life processes. Reactants may also be present in such low concentrations that it is unlikely they will meet and collide. Therefore, the rate of most biochemical reactions must be increased by a catalyst. A catalyst is a chemical that speeds up chemical reactions. In organisms, catalysts are called **enzymes**. Enzymes make a reaction faster with less energy.

Like other catalysts, enzymes are not reactants in the reactions they control. They help the reactants interact but are not used up in the reactions. Instead, they may be used over and over again. Unlike other catalysts, enzymes are usually highly specific for particular chemical reactions. They generally catalyze only one or a few types of reactions.

Enzymes are extremely efficient in speeding up reactions. They can catalyze up to several million reactions per second. As a result, the difference in rates of biochemical reactions with and without enzymes may be enormous. A typical biochemical reaction might take hours or even days to occur under normal cellular conditions without an enzyme but less than a second with the enzyme. For an animation of a reaction in the presence or absence of an enzyme, see http://www.stolaf.edu/people/giannini/flashanimat/enzymes/prox-orien.swf.

How Enzymes Work

How do enzymes speed up biochemical reactions so dramatically? Like all catalysts, enzymes work by lowering the activation energy of chemical reactions. This is illustrated in **Figure** 3.24. The biochemical reaction shown in the figure requires about three times as much activation energy without the enzyme as it does with the enzyme. An animation of this process can be viewed at http://www.stolaf.edu/people/giannini/flashanimat/enzymes/transition%20state.swf.

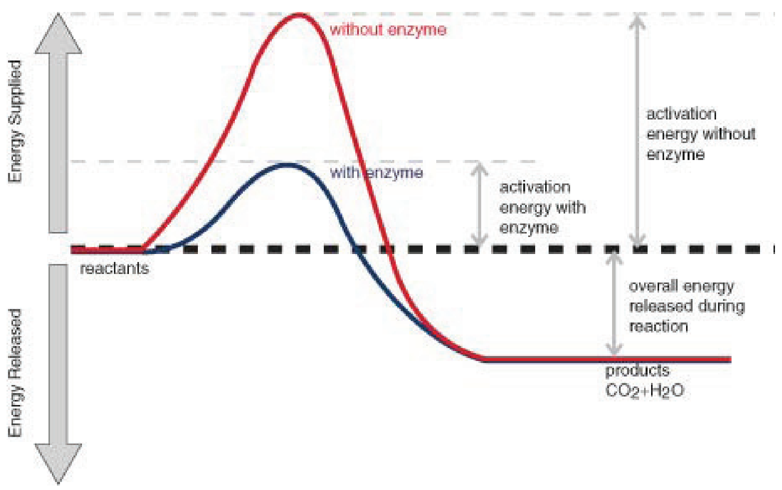


FIGURE 3.23

Enzymes generally lower activation energy by reducing the energy needed for reactants to come together and react. For example:

- Enzymes bring reactants together so they don't have to expend energy moving about until they collide at random. Enzymes bind both reactant molecules (called substrate), tightly and specifically, at a site on the enzyme molecule called the active site (**Figure** 3.25).
- By binding reactants at the active site, enzymes also position reactants correctly, so they do not have to overcome intermolecular forces that would otherwise push them apart. This allows the molecules to interact with less energy.

- Enzymes may also allow reactions to occur by different pathways that have lower activation energy.

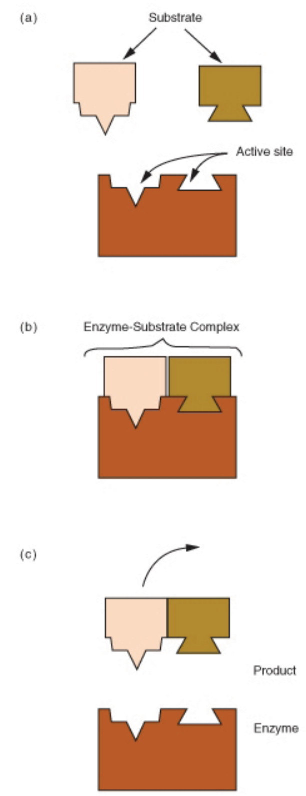


FIGURE 3.24

The activities of enzymes also depend on the temperature, ionic conditions, and the pH of the surroundings.

Some enzymes work best at acidic pHs, while others work best in neutral environments.

- Digestive enzymes secreted in the acidic environment (low pH) of the stomach help break down proteins into smaller molecules. The main digestive enzyme in the stomach is pepsin, which works best at a pH of about 1.5 (see the *Digestive and Excretory Systems* chapter). These enzymes would not work optimally at other pHs. Trypsin is another enzyme in the digestive system which break protein chains in the food into smaller parts. Trypsin works in the small intestine, which is not an acidic environment. Trypsin's optimum pH is about 8.
- Biochemical reactions are optimal at physiological temperatures. For example, most biochemical reactions work best at the normal body temperature of 98.6˚F. Many enzymes lose function at lower and higher temperatures. At higher temperatures, an enzyme's shape deteriorates and only when the temperature comes back to normal does the enzyme regain its shape and normal activity.

Importance of Enzymes

Enzymes are involved in most of the chemical reactions that take place in organisms. About 4,000 such reactions are known to be catalyzed by enzymes, but the number may be even higher. Needed for reactions that regulate cells, enzymes allow movement, transport materials around the body, and move substances in and out of cells.

In animals, another important function of enzymes is to help digest food. Digestive enzymes speed up reactions that break down large molecules of carbohydrates, proteins, and fats into smaller molecules the body can use (*See*

Chapter: Digestive and Excretory Systems). Without digestive enzymes, animals would not be able to break down food molecules quickly enough to provide the energy and nutrients they need to survive.

Lesson Summary

- A chemical reaction is a process that changes some chemical substances into others. It involves breaking and forming chemical bonds. Types of chemical reactions include synthesis reactions and decomposition reactions.
- Rates of chemical reactions depend on factors such as the concentration of reactants and the temperature at which reactions occur. Both factors affect the ability of reactant molecules to react.
- Enzymes are needed to speed up chemical reactions in organisms. They work by lowering the activation energy of reactions.

Review Questions

1. Identify the roles of reactants and products in a chemical reaction.
2. How do enzymes work to speed up chemical reactions?
3. What is wrong with the chemical equation below? How could you fix it? $CH_4 + O_2 \rightarrow CO_2 + 2\ H_2O$
4. What type of reaction is represented by the following chemical equation? Explain your answer. $2\ Na + 2\ HCL \rightarrow 2\ NaCl + H_2$
5. Why do all chemical reactions require activation energy?
6. Explain why organisms need enzymes to survive.

Points to Consider

Most chemical reactions in organisms take place in an environment that is mostly water.

- What do you know about water?
- Are you aware that water has unique properties?
- Do you know how water behaves differently from most other substances on Earth?
- Do you know why water is necessary for life?

Vocabulary Students need to Learn:

Enzyme

Energy

Element

Atom

Covalent bond

Ionic bond

Hydrogen bond

Anion

Cation

Isotope

ion

Lipid

Carbohydrate

Protein

Amino Acid

Organic compound

Solvent

Cohesion

Adhesion

Solute

Polarity

Metabolism

Reactant

Product

Activation energy

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CHAPTER 4 Cell Theory, Cell Structures and Cellular Transportation- Edited

Chapter Outline

4.1 Introduction to Cells

Lesson Objectives

- Explain how cells are observed.
- Recall the cell theory.
- Explain the levels of organization in an organism.

Check Your Understanding

- What are the main characteristics of living things?
- Name the four main classes of organic molecules that are building blocks of life.

Introduction

How do lipids, carbohydrates, proteins, and nucleic acids come together to form a living organism? By forming a cell. These organic compounds are the raw materials needed for life, and a **cell** is the smallest unit of an organism that is still considered living. Cells are the basic units that make up every type of organism. Some organisms, like bacteria, consist of only one cell. Other organisms, like humans, consist of trillions of specialized cells working together. Even if organisms look very different from each other, if you look close enough you'll see that their cells have much in common. (Use of a microscope in **Figure** 4.1 helps to illustrate this.)

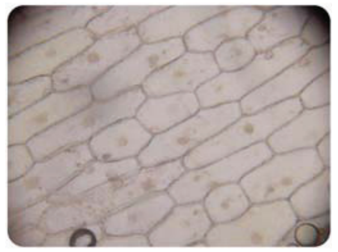

FIGURE 4.1
The outline of onion cells are visible under a light microscope.

Observing Cells

Most cells are so tiny that you can't see them without the help of a microscope. The microscopes that students typically use at school are light microscopes. Robert Hooke created a primitive light microscope in 1665 and observed cells for the very first time. Although the light microscope opened our eyes to the existence of cells, they are not useful for looking at the tiniest components of cells. Many structures in the cell are too small to see with a light microscope.

When scientists developed more powerful microscopes in the 1950s, the field of cell biology grew rapidly. A light microscope passes a light beam through a specimen, but the more powerful **electron microscope** passes a beam of electrons through the specimen, allowing a much closer look at the cell (**Figure** 4.2).

Transmission electron microscopes (TEM), which pass an electron beam through something, are used to look at a very thin section of an organism and allow us to study the internal structure of cells. **Scanning electron microscopes**

(SEM), which pass a beam of electrons across the surface of something, show the details of the shapes of surfaces, giving a 3D image.

Electron microscopes showed many small structures in the cell that had been previously invisible with light microscopes. One drawback to using an electron microscope is that it only images dead cells. A light microscope can be used to study living cells.

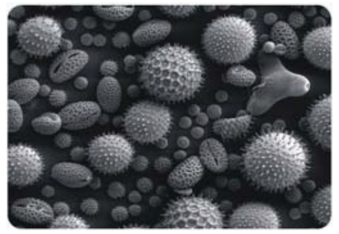

FIGURE 4.2
An electron microscope allows scientists to see much more detail than a light microscope, as with this sample of pollen. But a light microscope allows scientists to study living cells.

Cell Theory

In 1858, after microscopes had become much more sophisticated than Hooke's first microscope, Rudolf Virchow proposed that cells only came from other cells. For example, bacteria are composed of only one cell (**Figure** 4.3) and divide in half to replicate themselves. In the same way, your body makes new cells by the division of cells you already have. In all cases, cells only come from pre-existing cells.

This concept is central to the cell theory. **The cell theory** states that:

1. All organisms are composed of cells.
2. Cells are alive and the basic living units of organization in all organisms.
3. All cells come from other cells.

Credit for developing cell theory is usually given to three scientists: Theodor Schwann, who stated all animals are made of cells, Matthias Jakob Schleiden who stated all plants are made of cells, and Rudolf Virchow. In 1839, Schwann and Schleiden suggested that cells were the basic unit of life. Their theory accepted the first two tenets of modern cell theory. In 1855, Rudolf Virchow concluded that all cells come from pre-existing cells.

As with other scientific theories, the cell theory has been supported by thousands of experiments. And, since Virchow introduced the cell theory, no evidence has ever contradicted it.

FIGURE 4.3
Bacteria (pink) are an example of an organism consisting of only one cell.

Levels of Organization

Although cells share many of the same features and structures, as we will discuss in the next section, they also can be quite different. Each cell in your body is specialized for a specific task. For example:

- Red blood cells (**Figure** 4.4) are shaped with a pocket to increase their surface area for absorbing and releasing oxygen.
- Nerve cells, which can quickly transmit the sensation of touching a hot stove to your brain, are elongated and stringy to allow them to form a complex network with other nerve cells (**Figure** 4.5).
- Skin cells (**Figure** 4.6) are flat and fit tightly together.

As you can see, cells are shaped in ways that help them do their jobs. Multicellular (many-celled) organisms have many types of specialized cells in their bodies.

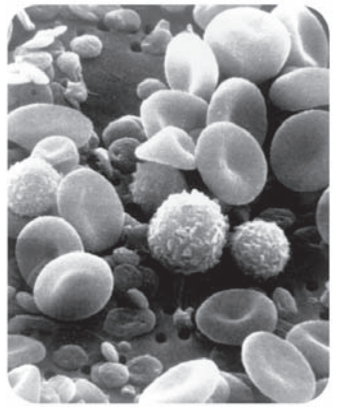

FIGURE 4.4
Red Blood cells are specialized to carry oxygen in the blood.

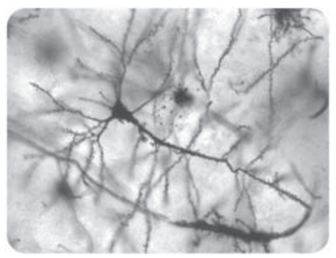

FIGURE 4.5
Neurons are shaped to conduct electrical impulses to many other nerve cells.

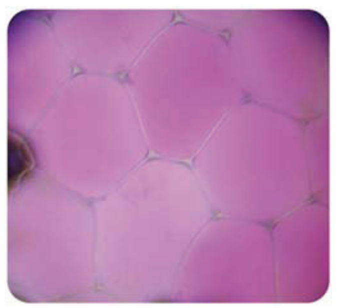

FIGURE 4.6
These epidermal cells make up the skin of plants. Note how the cells fit tightly together.

While cells are the basic units of an organism, groups of specialized cells can be organized into tissues. For example, your liver cells are organized into liver tissue, which is organized into an organ, your liver. Organs are formed from two or more specialized tissues working together for a common function. All organs, from your heart to your liver, are made up of an organized group of tissues.

These organs are part of a larger organization pattern, the organ systems. For example, your brain works together with your spinal cord and other nerves to form the nervous system. This organ system must be organized with other organ systems, such as the circulatory system and the digestive system, for your body to work. Organ systems

are coordinated together to form the complete organism. As you can see (**Figure** 4.7), there are many levels of organization in living things.

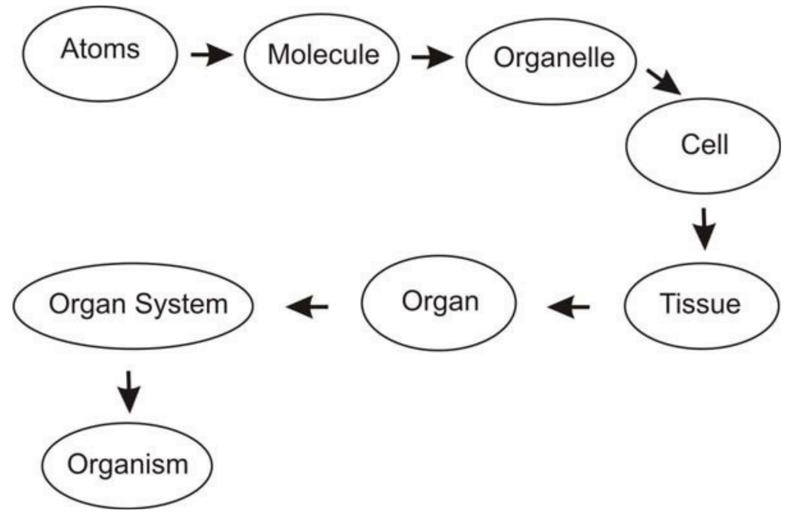

FIGURE 4.7
Levels of Organization, from the atom to the organism.

Lesson Summary

- Cells were first observed under the light microscope, but today electron microscopes allow scientists to take a closer look at the internal structures of cells
- The Cell Theory says that
  - all organisms are composed of cells;
  - cells are alive and the basic living units of organization in all organisms; and
  - All cells come from other cells.
- Cells are organized into tissues, which are organized into organs, which are organized into organ systems, which are organized to create the whole organism.

Review Questions

1. What are the three parts of the cell theory?
2. Which scientist first discovered cells?
3. Which scienctist stated that all animals are made up of cells?
4. According to the cell theory, can we synthesize a cell in the laboratory from organic molecules?
5. Do all cells work exactly the same?
6. Put the following in the correct order from simplest to most complex: organ, cell, tissue, organ system.

Points to Consider

- Do you think there would be a significant difference between bacteria cells and your brain cells? What might they be?
- Do you think a bacteria cell and brain cell have some things in common? What might they be?
- Do you think cells are organized? What would be the benefit of organization?

4.2 Cell Structure

Lesson Objectives

- Compare prokaryotic and eukaryotic cells.
- List the organelles of the cell and their functions.
- Discuss the structure and function of the cell membrane and cytosol.
- Describe the structure and function of the nucleus.
- Distinguish between plant and animal cells.

Check Your Understanding

- What is a cell?
- How do we visualize cells?

Introduction

Understanding the structure and function of cells is essential to understanding how living organisms work. Cell biology is central to all other fields of biology, including medicine. Many human diseases and disorders are caused by the malfunction of people's cells. Furthermore, toxins in the environment often act on specific cellular processes. The healthy functioning of the body and its organs is dependent on its smallest unit - the cell.

To better understand the biology of the cell, you will first learn to distinguish the two basic categories of all cells: prokaryotic and eukaryotic cells. You will also learn what makes a cell specialized; there are major differences between a "simple" cell, like a bacteria, and a "complex" cell, like a cell in your brain. To understand these differences, you need to first understand the basic components of the cell, which include the:

- Cell membrane
- Nucleus and chromosomes
- Other organelles

Prokaryotic and Eukaryotic Cells

There are two basic types of cells, **prokaryotic cells** (**Figure** 4.7), which include bacteria and archaea, and **eukaryotic cells** (**Figure** 4.8), which include all other cells. Prokaryotic cells are much smaller and simpler than eukaryotic cells; eukaryotic cells can be considered to be "specialized." Prokaryotic cells are surrounded by a **cell wall** that supports and protects the cell. In prokaryotic cells the DNA, the genetic material, forms a single large circle that coils up on itself. Prokaryotic cells also can contain extra small circles of DNA, known as **plasmids**.

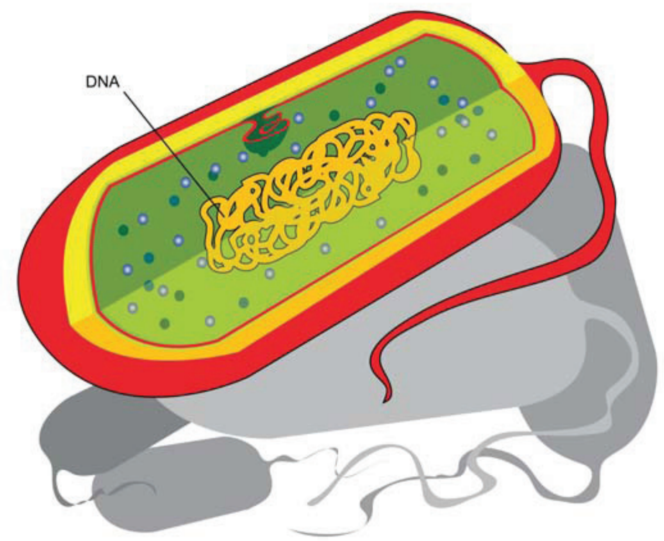

FIGURE 4.8

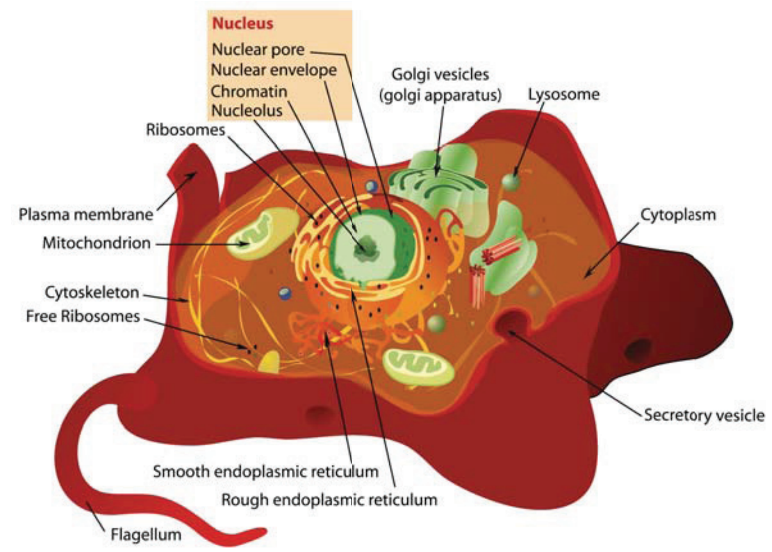

FIGURE 4.9

TABLE 4.1: Comparison of Prokaryotic and Eukaryotic Cells

Feature	Prokaryotic cells	Eukaryotic cells
DNA	Single "naked" circle; plasmids	In membrane-enclosed nucleus; chromosomes
Membrane-enclosed organelles	No	Yes
Examples	Bacteria	Plants, animals, fungi, protists

The main difference between eukaryotic and prokaryotic cells is that eukaryotic cells store their DNA in a membrane-enclosed **nucleus**. The presence of a nucleus is the primary distinguishing feature of a eukaryotic cell. In addition to the nucleus, eukaryotic cells have other subcompartments, small membrane-enclosed structures called **organelles**. Membrane-enclosed organelles and a nucleus are absent in prokaryotic cells. Eukaryotic cells include the cells of

fungi, animals, protists, and plants.

The Plasma Membrane and Cytosol

Both eukaryotic and prokaryotic cells have a plasma membrane. The **plasma membrane** is a double layer of specialized lipids, known as phospholipids, along with many special proteins. The function of the plasma membrane, also known as the "cell membrane," is to control what goes in and out of the cell.

Some molecules can go through the cell membrane in and out of the cell and some can't, so biologists say the membrane is **semipermeable**. It is almost as if the membrane chooses what enters and leaves the cell.

The cell membrane gives the cell an inside that is separate from the outside world. Without a cell membrane, the parts of a cell would just float away. A cell needs a boundary even more than we need our skin. Without a cell membrane, a cell would be unable to maintain a stable internal environment separate from the external environment, what we call homeostasis.

Eukaryotic and prokaryotic cells also share an internal fluid-like substance called the **cytosol**. The cytosol is composed of water and other molecules, including enzymes that speed up the cell's chemical reactions. Everything in the cell - the nucleus and the organelles - sit in the cytosol. The term **cytoplasm** refers to the cytosol and all the organelles, but not the nucleus.

TABLE 4.2: **Eukaryotic Organelles**

Organelle	**Function**
Ribosomes	Involved in making proteins
Golgi apparatus	Packages proteins and some polysaccharides
Mitochondria	Makes ATP
Endoplasmic Reticulum	Makes lipids, transports
*Chloroplast	Makes sugar (photosynthesis)
Lysosomes	Digests macromolecules

TABLE 4.3:

*Cell Wall	Support, structure
Cell Membrane	Regulates input & output; semipermeable
Vacuole	Storage
Cytoplasm	Fluid that contains organelles
Cytoskeleton	Internal structure of cell

TABLE 4.4:

Centriole	Aides in cell division

The Nucleus and Chromosomes

The nucleus, which is found exclusively in eukaryotic cells, is a membrane-enclosed structure that contains most of the genetic material of the cell (**Figure** 4.9). Like a library, it holds vital information, mainly detailed instructions for building proteins. The **nuclear envelope**, a double membrane that surrounds the nucleus, controls which molecules go in and out of the nucleus.

Inside the nucleus are the chromosomes, the DNA all wrapped in special proteins. The genetic information on the chromosomes is stored made it available to the cell when necessary and also duplicated when it is time to pass the genetic information on when a cell divides. All the cells of a species carry the same number of chromosomes. For example, human cells each have 23 pairs of chromosomes. Each chromosome in turn carries hundreds or thousands of genes that encode proteins that help determine traits as varied as tooth shape, hair color, or kidney function.

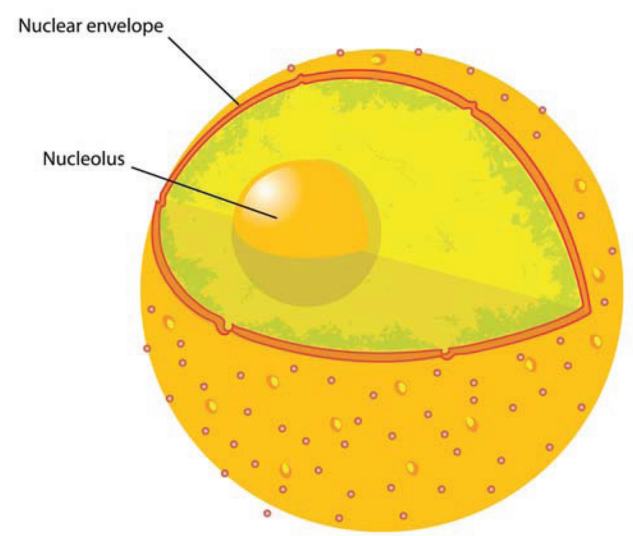

FIGURE 4.10

The Cell Factory

Just as a factory is made up of many people, machines, and specific areas, each part of the whole playing a different role, a cell is also made up of different parts, each with a special role. For example, the nucleus of a cell is like a safe containing the factory's trade secrets, including how to build thousands of proteins, how much of each one to make, and when. The **mitochondria** are powerhouses that generate the ATP needed to power chemical reactions. Plant cells have special organelles called **chloroplasts** that capture energy from the sun and store it in the chemical bonds of sugar molecules - in the process called photosynthesis (**Figure** 4.10). (The cells of animals and fungi do not photosynthesize and do not have chloroplasts.)

The **vacuoles** are storage centers, and the **lysosomes** are the recycling trucks that carry waste away from the factory. Inside lysosomes are enzymes that break down old molecules into parts that can be recycled into new ones. Eukaryotic cells also contain and internal skeleton called the **cytoskeleton**. Like our bony skeleton, a cell's cytoskeleton gives the cell a shape and helps it move parts of the cell.

In both eukaryotes and prokaryotes, **ribosomes** are where proteins are made. Some ribosomes cluster on folded membranes called the endoplasmic reticulum (ER). If the ER is covered with ribosomes, it looks bumpy and is called rough ER. If the ER lacks ribosomes, it is smooth and is called smooth ER. Proteins are made on rough ER and lipids are made on smooth ER.

Another set of folded membranes in cells is the **Golgi apparatus**, which works like a mail room. The Golgi apparatus receives the proteins from the rough ER, puts sugar molecule "shipping addresses" on the proteins, packages them up in vesicles, and then sends them to the right place in the cell.

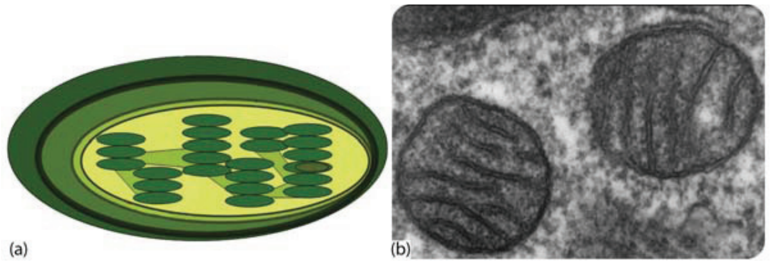

FIGURE 4.11

Plant Cells

Even though plants and animals are both eukaryotes, plant cells differ in some ways from animal cells. First, plant cells are unique in having a large central **vacuole** that holds a mixture of water, nutrients, and wastes. A plant cell's vacuole can make up 90% of the cell's volume. In animal cells, vacuoles are much smaller.

Second, plant cells have a cell wall, which animal cells do not. A **cell wall** gives the plant cell strength, rigidity, and protection. Although bacteria and fungi also have cell walls, a plant cell wall is made of a different material. Plant cell walls are made of the polysaccharides cellulose, fungal cell walls are made of chitin, and bacterial cell walls are made of peptidoglycan. This is highlighted in **Figure** 4.11.

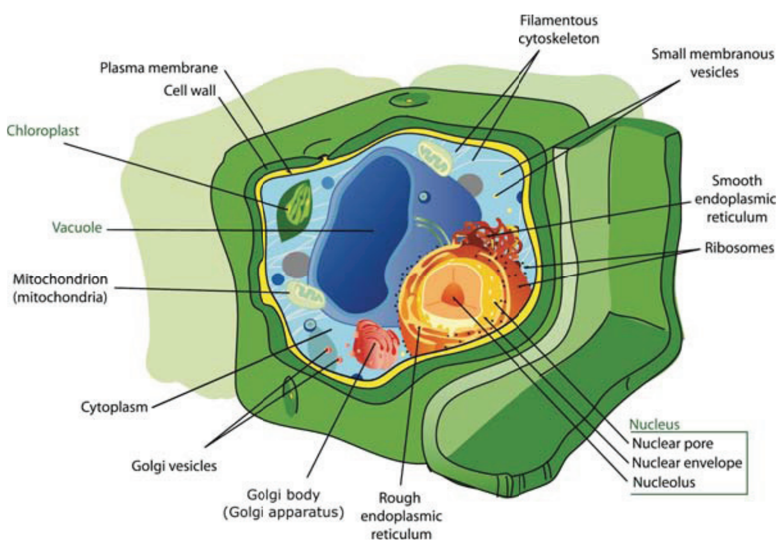

FIGURE 4.12

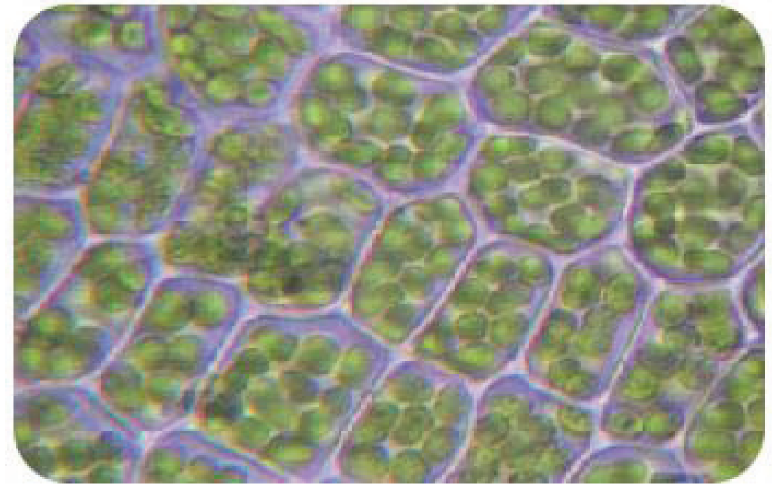

FIGURE 4.13

A third difference between plant and animal cells is that plants have several kinds of organelles called **plastids**. There are several kinds of plastids, including **chloroplasts**, needed for photosynthesis; **leucoplasts**, which store starch and oil; and brightly colored **chromoplasts**, which give some flowers and fruits their yellow, orange, or red color. Under a microscope one can see plant cells more clearly (**Figure** 4.12).

Lesson Summary

- Prokaryotic cells lack a nucleus; eukaryotic cells have a nucleus.
- Each component of a cell has a specific function.
- Plant cells have unique features including plastids, cell walls, and central vacuoles.

Review Questions

1. What are the two basic types of cells?
2. What are organelles?
3. Discuss the main differences between prokaryotic cells and eukaryotic cells.
4. What is the plasma membrane and what is its role?
5. What organelle is known as the "powerhouse" of the cell?
6. Why does photosynthesis not occur in animal cells?
7. What are the main differences between a plant cell and an animal cell?

Points to Consider

- Think about what molecules would need to be transported into cells.
- Discuss why it would be important for some molecules to be kept out of a cell.

4.3 Transport

Lesson Objectives

- Describe several methods of transporting molecules and ions into and out of the cell.
- Distinguish between active and passive transport.
- Explain how diffusion and osmosis work.

Check Your Understanding

- What structure surrounds the cell?
- What is the primary component of the cell membrane?
- What does homeostasis mean?

Introduction

All organisms and their cells need to maintain homeostasis. But how can a cell keep a stable internal environment when the environment around the cell is constantly changing? Obviously, the cell needs to separate itself from the external environment. This job is accomplished by the cell membrane. The cell membrane is **selectively permeable,** or "semipermeable," which means that only some molecules can get through the membrane. If the cell membrane was completely permeable, the inside of the cell would be about the same as the outside and the cell could not achieve homeostasis.

How does the cell maintain this selective permeability? How does the cell control what molecules enter and leave the cell? The ways that cells control what passes through the cell membrane will be the focus of this lesson.

What is Transport?

The selectively permeable nature of the plasma membrane is due in part to the chemical composition of the membrane. Recall that the membrane is a double layer of phospholipids (a "bilayer") embedded with proteins (**Figure** 4.13). A single phospholipid molecule has a hydrophilic, or water-loving, head and hydrophobic, or water-fearing, tail. The hydrophilic heads face the inside and outside of the cell, where water is abundant. The water-fearing, hydrophobic tails face each other in the middle of the membrane. At body temperature, the plasma membrane is fluid and constantly moving, like a soap bubble; it is not a solid structure.

Water and small non-charged molecules such as oxygen and carbon dioxide can pass freely through the membrane by slipping around the phospholipids. But larger molecules and charged molecules cannot pass through the plasma membrane easily. Therefore, special methods are needed for transporting some molecules across the plasma membrane and into or out of the cell.

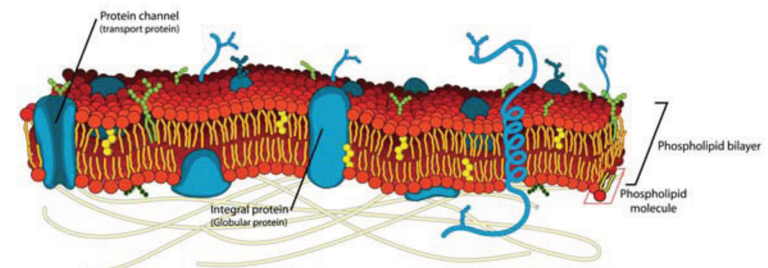

FIGURE 4.14

Since atoms have an equal number of protons and electrons, they have no net charge. The negative charges of the electrons balance out the positive charges of the protons. Many molecules have an equal number of electrons and protons, so we call them non-polar molecules. However, some atoms can lose or gain electrons easily, giving them a positive or negative charge. These charged particles are called **ions.** If an atom loses an electron, it becomes a positively charged ion, such as the sodium ion Na^+. If an atom gains an electron, it will be a negatively charged ion, such as the chloride ion, Cl^-. Na^+ and Cl^- readily form NaCl, or common table salt. Since Na^+ and Cl^- are charged, they are unable to pass freely through the plasma membrane.

Passive Transport

Small molecules can pass through the plasma membrane through a process called diffusion. **Diffusion** is the movement of molecules from an area where there is a higher concentration (larger amount) of the substance to an area where there is a lower concentration (lower amount) of the substance. The amount of a substance in relation to the volume, is called **concentration**. Diffusion requires no energy input from the cell (**Figure** 4.14). Diffusion occurs by the random movement of molecules; molecules move in both directions (into and out of the cell), but there is a greater movement from an area of higher concentration towards an area of lower concentration. The movement of the substance from a greater concentration to a lesser concentration is referred to as moving down the concentration gradient. For example, oxygen diffuses out of the air sacs in your lungs into your bloodstream because oxygen is more concentrated in your lungs than in your blood. Oxygen moves down the concentration gradient from your lungs into your bloodstream

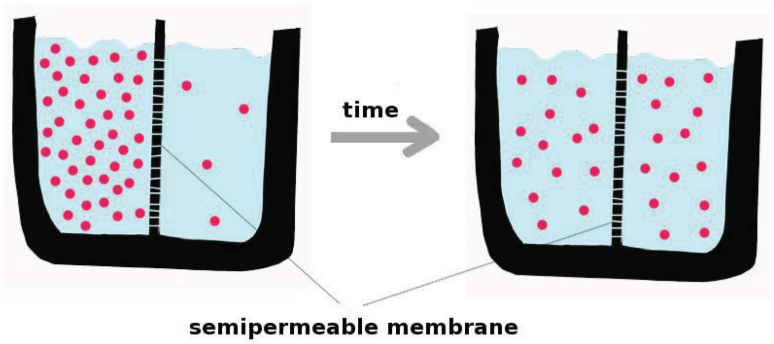

FIGURE 4.15

The diffusion of water across a membrane due to concentration differences is called **osmosis.** If a cell is placed in a **hypotonic solution,** meaning the solution has a lower concentration of dissolved material than what is inside the cell, water will move into the cell. This causes the cell to swell, and it may even burst. Organisms that live in fresh water, which is a hypotonic solution, have to prevent too much water from coming into their cells. Freshwater fish excrete a large volume of dilute urine to rid their bodies of excess water.

If a cell is placed in a **hypertonic solution,** meaning there is more dissolved material in the outside environment than in the cell, water will leave the cell. That can cause a cell to shrink and shrivel. Marine animals live in salt water, which is a hypertonic environment; there is more salt in the water than in their cells. To prevent losing too much water from their bodies, these animals intake large quantities of salt water and secrete salt by active transport, which will be discussed later in this lesson.

To keep cells intact, they need to be placed in an **isotonic solution,** a solution in which the amount of dissolved material is equal both inside and outside the cell. Therefore, there is no net movement of water into or out of the cell. Water still flows in both directions, but an equal amount enters and leaves the cell. In the medical setting, red blood cells can be kept intact in a solution that is isotonic to the blood cells. If the blood cells were put in pure water, the solution would be hypotonic to the blood cells, so the blood cells would swell and burst. This is represented in the **Figure** 4.15.

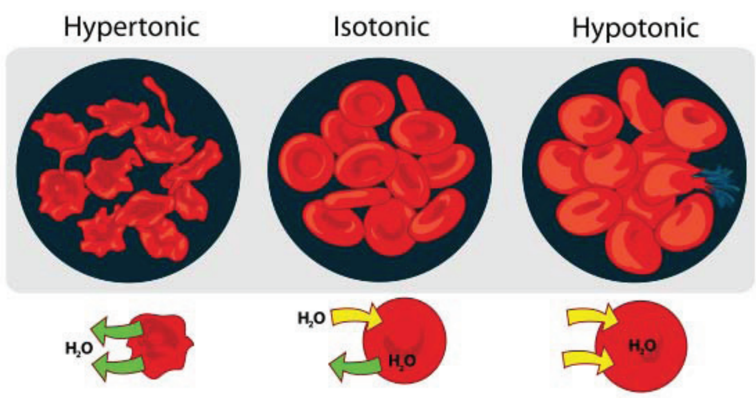

FIGURE 4.16

Sometimes diffusion across the membrane is slow or even impossible for some charged or large molecules. These molecules need the help of special helper proteins that are located in the plasma membrane. **Ion channel proteins** move ions across the plasma membrane. Other molecules, such as glucose, move across the cell membrane by **facilitated diffusion,** in which a carrier protein physically moves the molecule across the membrane (**Figure** 4.16). Both channel proteins and carrier proteins are specific for the molecule transported. Movement by ion channel proteins and facilitated diffusion are still considered **passive transport,** meaning they move molecules down the cell's concentration gradient and do not require any energy input.

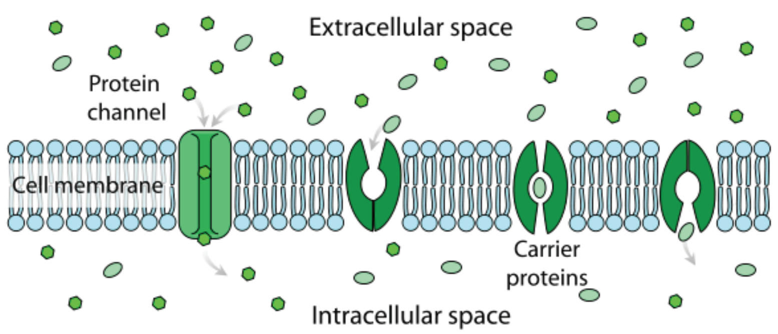

FIGURE 4.17

Active Transport

During active transport, molecules move against the concentration gradient, toward the area of higher concentration. This is the opposite of diffusion. Active transport requires both an input of energy, in the form of ATP, and a carrier protein to move the molecules. These proteins are often called pumps, because, as a water pump uses energy to force water against gravity, proteins involved in active transport use energy to move molecules against their concentration gradient.

There are many examples of why active transport is important in your cells. One example occurs in your nerve cells. In these cells, the **sodium-potassium pump** (**Figure** 4.17) moves sodium out of the cell and potassium into the cell, both against their concentration gradients.

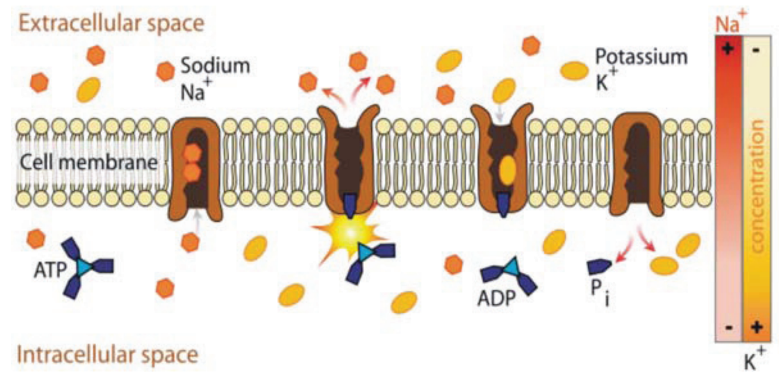

FIGURE 4.18

Transport Through Vesicles

Some large molecules are just too big to move across the membrane, even with the help of a carrier protein. These large molecules must be moved through vesicle formation, a process by which the large molecules are packaged in a small bubble of membrane for transport. This process keeps the large molecules from reacting with the cytoplasm of the cell. Vesicle formation does require an input of energy, however.

There are several kinds of vesicle formation that allow large molecules to move across the plasma membrane. **Exocytosis** moves large molecules outside of the cell. During exocytosis, the vesicle carrying the large molecule fuses with the plasma membrane. The large molecule is then released outside of the cell, and the vesicle is absorbed into the plasma membrane. **Endocytosis** is the process by which cells take in large molecules by vesicle formation. Types of endocytosis include phagocytosis and pinocytosis. **Phagocytosis** moves large substances, even another cell, into the cell. Phagocytosis occurs frequently in single-celled organisms, such as amoebas. **Pinocytosis** (**Figure** 4.18) involves the movement of liquid or very small particles into the cell. These processes cause some membrane material to be lost as these vesicles bud off and come into the cell. This membrane is replaced by the membrane gained through exocytosis.

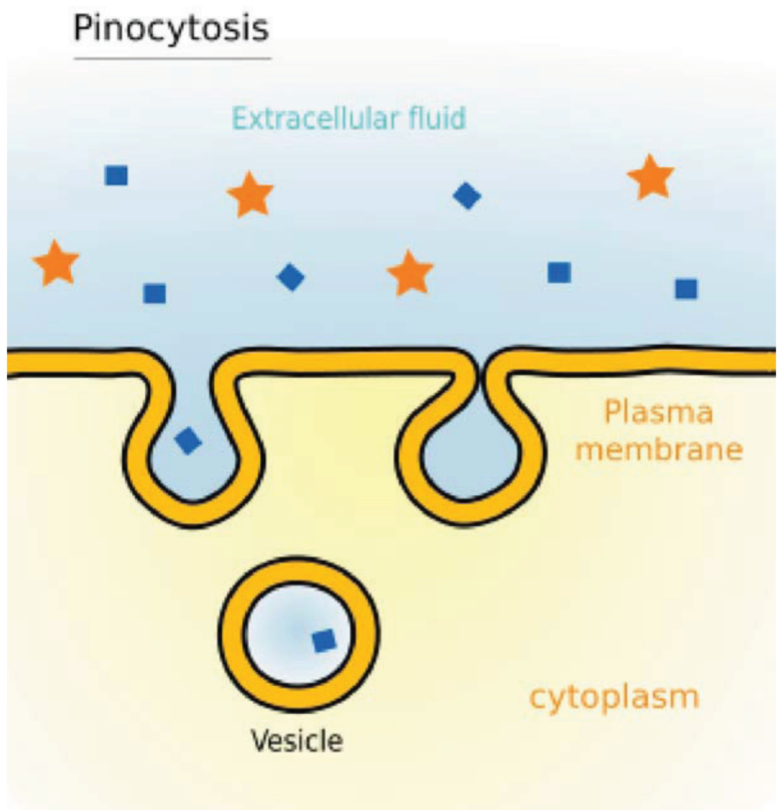

FIGURE 4.19

Lesson Summary

- The plasma membrane is selectively permeable or semi-permeable, meaning that some molecules can move through the membrane easily, while others require specialized transport mechanisms.
- Passive transport methods, including diffusion, ion channels, facilitated diffusion, and osmosis, move molecules in the direction of the lowest concentration of the molecule and do not require energy.
- Active transport methods move molecules in the direction of the higher concentration and require energy and a carrier protein.
- Vesicles can be used to move large molecules, which requires energy input.

Review Questions

1. What happens when a cell is placed in a hypotonic solution?
2. What happens when a cell is placed in a hypertonic solution?
3. What's the main difference between active and passive transport?
4. List an example of active transport.
5. List the types of passive transport.
6. Why is the plasma membrane considered semipermeable?
7. What is the process where a cell engulfs a macromolecule, forming a vesicle?
8. What is diffusion?
9. Explain the results of a sodium-potassium pump working across a membrane.
10. Does facilitated transport move a substance down or up a gradient?

Points to Consider

- The next lesson discusses photosynthesis.
- It is often said that plants make their own food. What do you think this means?
- What substances would need to move into a leaf cell?
- What substances would need to move out of a leaf cell?

Vocabulary that Students need to Learn

Organelles

Cell Membrane

Nucleus

Cell wall

Ribosome

Golgi Apparatus

Endoplasmic Reticulum

Mitochondria

Cholorplast

Lysosomes

Cytoskeleton

Cytoplasm

Vacuole

Centriole

Microorganism

Osmosis

Diffusion

Active Transport

Cell Theory

4.4 References

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4. . LS_eukaryotic.
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CHAPTER 5 Energy Production in Cells - Edited

Chapter Outline

5.1 Cellular Energy

Lesson 4.1: ATP

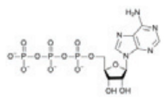
Objectives

- Describe the structure of ATP and how it makes ATP energetic
- List the processes that use ATP as a source of energy

Check your understanding

- Is phosphate a very stable element, and how can you tell?

TABLE 5.1:

Adenosine triphosphate


Overview of ATP

Adenosine-5'-triphosphate (**ATP**) is the energy source for cells. It was proposed to be the main energy-transfer molecule in the cell by Fritz Albert Lipmann in 1941. ATP transports chemical energy within cells for metabolism. It is produced by photosynthesis and cellular respiration and used by enzymes and structural proteins in many cellular processes like cell division and active transport. One molecule of ATP contains three phosphate groups, and it is produced by ATP synthase from inorganic phosphate and adenosine diphosphate (ADP).

Metabolic processes that use ATP as an energy source convert it back into its ADP. ATP is therefore continuously recycled in organisms: the human body turns over its own weight in ATP each day.

5.2 Photosynthesis

Lesson Objectives

- Explain the importance of photosynthesis.
- Write and interpret the chemical equation for photosynthesis.
- Describe what happens during the light reactions and the Calvin Cycle.

Check Your Understanding

- How are plant cells different from animal cells?
- In what organelle does photosynthesis take place?

Introduction

Almost all life on Earth depends on photosynthesis. Recall that photosynthesis is the process by which plants use the sun's energy to make their own "food" from carbon dioxide and water. For example, animals, such as caterpillars, eat plants and therefore rely on the plants to obtain energy. If a bird eats a caterpillar, then the bird is obtaining the energy that the caterpillar gained from the plants. So the bird is indirectly getting energy that began with the "food" formed through photosynthesis. Almost all organisms obtain their energy from photosynthetic organisms, either directly, by eating photosynthetic organisms, or indirectly by eating other organisms that ultimately obtained their energy from photosynthetic organisms. Therefore, the process of photosynthesis is central to sustaining life on Earth.

Overview of Photosynthesis

Photosynthesis is the process that converts the energy of the sun, or solar energy, into carbohydrates, a type of chemical energy. During photosynthesis, carbon dioxide and water combine with solar energy, yielding glucose (the carbohydrate) and oxygen. As mentioned previously, plants can photosynthesize, but plants are not the only organisms with this ability. Algae, which are plant-like protists, and cyanobacteria (certain bacteria which are also known as blue-green bacteria, or blue-green algae) can also photosynthesize. Algae and cyanobacteria are important in aquatic environments as sources of food for larger organisms.

Photosynthesis mostly takes place in the leaves of a plant. The green pigment in leaves, **chlorophyll,** helps to capture solar energy. And special structures within the leaves provide water and carbon dioxide, which are the raw materials for photosynthesis. The veins within a leaf carry water which originates from the roots, and carbon dioxide enters the leaf from the air through special pores called **stomata** (**Figure** 5.1).

The water and carbon dioxide are transported within the leaf to the **chloroplast** (**Figure** 5.2), the organelle in which photosynthesis takes place. The chloroplast has two distinct membrane systems; an outer membrane surrounds the chloroplast and an inner membrane system forms flattened sacs called **thylakoids.** As a result, there are two separate spaces within the chloroplast. The interior space that surrounds the thylakoids is filled with a fluid called **stroma.** The inner compartments formed by the thylakoid membranes are called the thylakoid space.

The overall chemical reaction for photosynthesis is 6 molecules of carbon dioxide (CO_2) and 6 molecules of water (H_20), with the addition of solar energy, yields 1 molecule of glucose ($C_6H_{12}O_6$) and 6 molecules of oxygen (O_2). Using chemical symbols the equation is represented as follows:

FIGURE 5.1
Stomata are special pores that allow gasses to enter and exit the leaf.

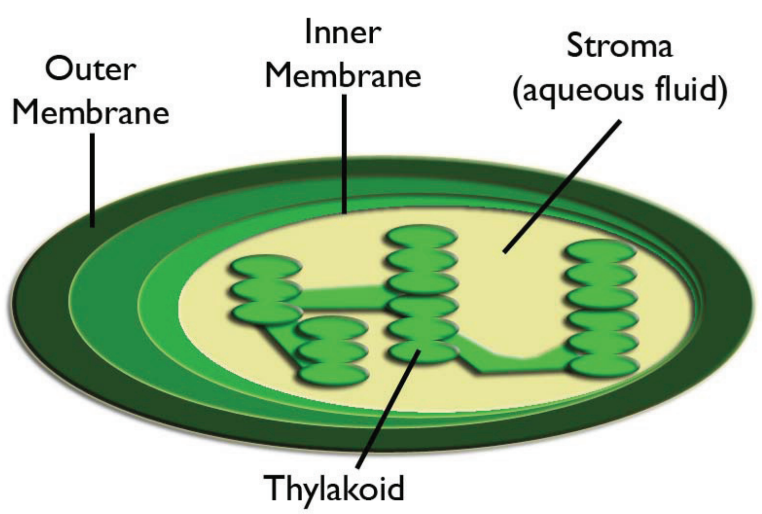


FIGURE 5.2
The chloroplast is the photosynthesis factory of the plant.

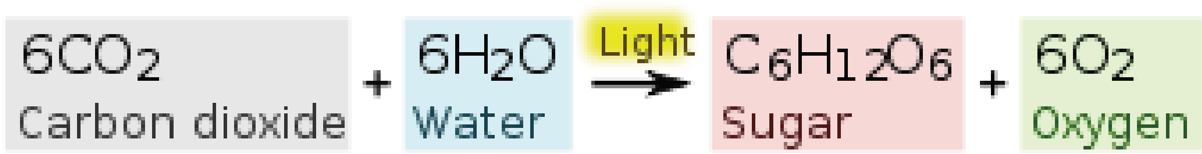


FIGURE 5.3
Oxygen: An Essential Byproduct

Oxygen: An Essential Byproduct

Oxygen is a byproduct of the process of photosynthesis and is released to the atmosphere through the stomata. Therefore, plants and other photosynthetic organisms play an important ecological role in converting carbon dioxide into oxygen. As you know, animals need oxygen to carry out the energy-producing reactions of their cells. Without photosynthetic organisms, many other organisms would not have enough oxygen in the atmosphere to survive. Oxygen is also used as a reactant in cellular respiration, which is discussed in the next lesson, so essentially, oxygen cycles through the processes of photosynthesis and cellular respiration.

The Light Reactions and the Calvin Cycle

The overall process of photosynthesis does not happen in one step, however. The chemical equation of photosynthesis shows the results of many chemical reactions. The chemical reactions that make up the process of photosynthesis can be divided into two groups: the light reactions (also known as the light-dependent reactions, because these reactions only occur during daylight hours) and the Calvin Cycle, or the light-independent reactions. During the **light reactions**, the energy of sunlight is captured, while during the **Calvin Cycle**, carbon dioxide is converted into glucose, which is a type of sugar. This is summarized in **Figure** below.

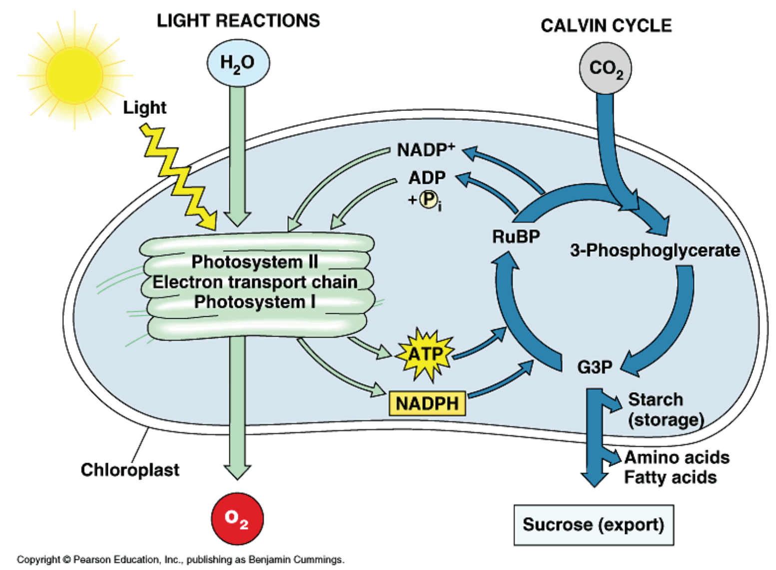


FIGURE 5.4

Stage 1: Capturing Light Energy

In the first step of the light reactions, solar energy is absorbed by the chlorophyll (and accessory pigments) within the chloroplast's thylakoid membranes. This absorbed energy excites electrons in the thylakoid membranes. The electrons are then transferred from the thylakoid membranes by a series of electron carrier molecules. The series of electron carrier molecules that transfers electrons is called the electron transport chain. During this process water molecules in the thylakoid are split to replace the electrons that left the pigment, releasing oxygen and adding hydrogen ions (H^+) to the thylakoid space. As the thylakoid becomes a reservoir for hydrogen ions, a **chemiosmotic gradient** forms as there are more hydrogen ions in the thylakoid than in the stroma. As H^+ ions flow from the high concentration in the thylakoid to the low concentration in the stroma, they provide energy as they pass through an enzyme called ATP synthase. ATP synthase uses the energy of the movement of H^+ ions to make ATP. Meanwhile, highly energized electrons from the electron transport chain combine with the electron carrier $NADP^+$ to become NADPH (**Figure** 4.3). NADPH will carry this energy in the electrons to the next phase of photosynthesis, the Calvin Cycle.

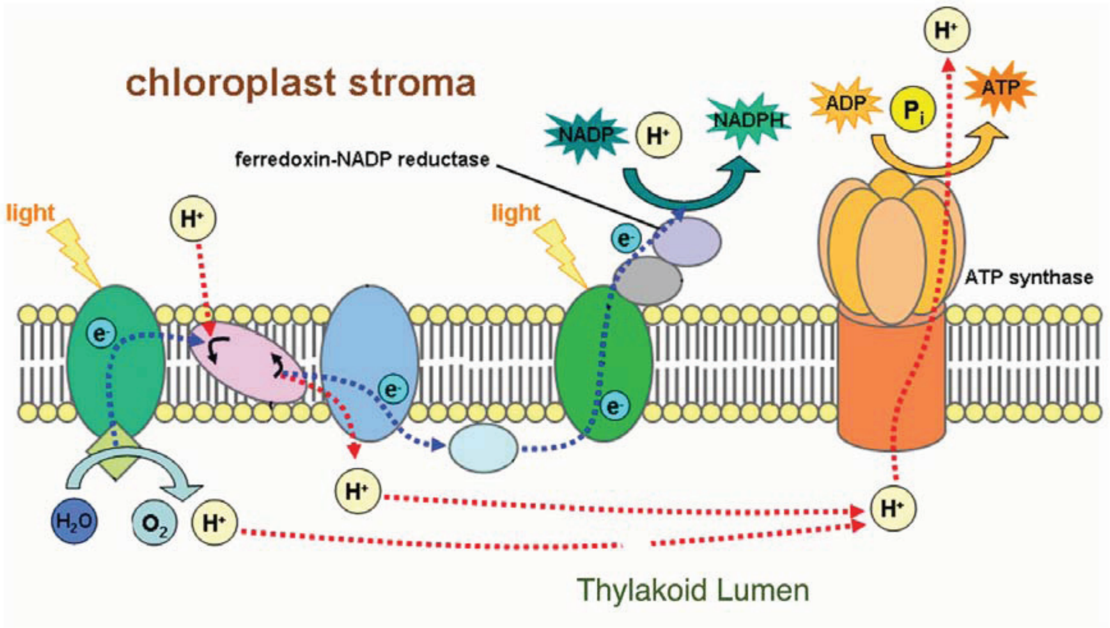


FIGURE 5.5
The light reactions include the movement of electrons down the electric transport chain, splitting water and releasing hydrogen ions into the thylakoid space. Steps of the Light reaction: 1st: light hits chlorophyll 2nd: electrons are excited 3rd: Water is split into Oxygen & Hydrogen ions 4th: Hydrogen ion gradient produced 5th: Hydrogens move through ATP synthase producing ATP 6th: Hydrogens from ATP synthase combines with NADP to form NADPH

Stage 2: Producing Food

During the Calvin Cycle, which occurs in the stroma of the chloroplast, glucose is formed from carbon dioxide and the products of the light reactions. During the first step CO_2 is attached to a 5-carbon molecule (called Ribulose-5-Phosphate, RuBP), forming a 6-carbon molecule. This reaction is catalyzed by an enzyme named RuBisCo, which is the most abundant protein in plants and maybe on Earth! The 6-carbon molecule formed by this reaction immediately splits into two 3-carbon molecules, and the 3-carbon molecule is rearranged to a 3-carbon carbohydrate. The energy and electrons needed for this process are provided by the ATP and NADPH produced earlier in photosynthesis. The "food" made by photosynthesis is formed from the 3-carbon carbohydrate. Two 3-carbon carbohydrates combine to form glucose, a 6-carbon carbohydrate. Next, the 6-carbon RuBP must be reproduced so the Calvin Cycle can start again (**Figure** 4.5).

The 3-carbon product of the Calvin Cycle can be converted into many types of organic molecules. Glucose, the energy source of plants and animals, is only one possible product of photosynthesis. Glucose is formed by two turns of the Calvin Cycle. Glucose can be formed into long chains as **cellulose**, a structural carbohydrate, or **starch**, a long-term storage carbohydrate. The product of the Calvin Cycle can also be used as the backbone of fatty acids, or amino acids, which make up proteins.

Photosynthesis is crucial to most ecosystems since animals obtain energy by eating other animals, or plants and seeds that contain these organic molecules. In fact, it is the process of photosynthesis that supplies almost all the

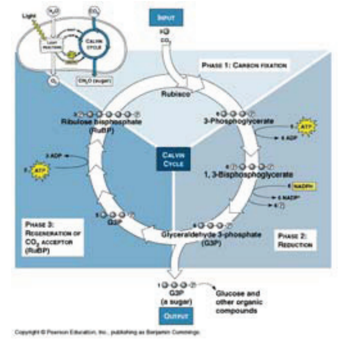


FIGURE 5.6
The Calvin Cycle begins with carbon fixation, or carbon dioxide attaching to the 5-carbon molecule RuBP, forming a 6-carbon molecule and splitting immediately in to two 3-carbon molecules. This is shown at the top of the figure. This carbon molecule is then reduced to a 3-carbon carbohydrate, shown at the bottom of the figure. The energy and reducing power needed for this process are provided by the ATP and NADPH produced from the light reactions. Next, RuBP must be reproduced so the Calvin Cycle can continue. After 2 cycles Glucose is the final product.

energy to an ecosystem.

Lesson Summary

- The net reaction for photosynthesis is that carbon dioxide and water, together with energy from the sun, produce glucose and oxygen.
- During the light reactions of photosynthesis, solar energy is converted into the chemical energy of ATP and NADPH.
- During the Calvin Cycle, the chemical energy of ATP and NADPH is used to convert carbon dioxide into glucose.

Review Questions

1. What is the energy-capturing stage of photosynthesis?
2. What are the products of the light reactions?
3. What are the ATP and NADPH from the light reactions used for?
4. Where does the oxygen released by photosynthesis come from?
5. What happens to the glucose produced from photosynthesis?
6. Describe the structures of the chloroplast where photosynthesis takes place.
7. What is the significance of the electron transport chain?
8. What are the reactants required for photosynthesis?
9. What are the products of photosynthesis?

Points to Consider

- How is glucose turned into an usable form of energy called ATP?
- How do you gain energy from the food you eat?
- What would provide more energy- a bowl of pasta or a small piece of candy?
- What “waste” gas do you exhale?

5.3 Cellular Respiration

Lesson Objectives

- Write and explain the chemical formula for cellular respiration.
- Explain the two states of cellular respiration.
- Compare photosynthesis with cellular respiration.
- Describe the results of fermentation and understand when fermentation is needed.

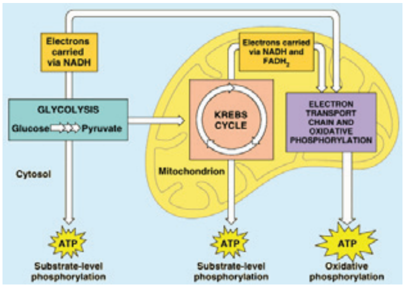
Check Your Understanding

- Where does the energy captured at the beginning of photosynthesis originate from?
- What is the form of chemical energy produced by photosynthesis?

Introduction

How does the food you eat provide energy? When you need a quick boost of energy, you might reach for an apple or a candy bar. Although foods with sugars can give you a quick boost of energy, they cannot be used for energy directly by your cells. Energy is simply stored in these foods. Through the process of **cellular respiration,** the energy in food is converted into energy that can be used by the body's cells. In other words, glucose (and oxygen) is converted into ATP (and carbon dioxide and water). ATP is the molecule that provides energy for your cells to perform work, such as contracting your muscles as you walk down the street or performing active transport. Cellular respiration is simply a process that converts one type of chemical energy, the energy stored in sugar, into another type, ATP.

Overview of Cellular Respiration



Most often, cellular respiration proceeds by breaking down glucose into carbon dioxide and water. As this breakdown of glucose occurs, energy is released. The process of cellular respiration includes the conversion of this energy into ATP. The overall reaction for cellular respiration is as follows:

$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$

Notice that the equation for cellular respiration is the direct opposite of photosynthesis. While water was broken down to form oxygen during photosynthesis, in cellular respiration oxygen is combined with hydrogen to form water. While photosynthesis requires carbon dioxide and releases oxygen, cellular respiration requires oxygen and releases

carbon dioxide. This exchange of carbon dioxide and oxygen in all the organisms that use photosynthesis and/or cellular respiration worldwide, helps to keep atmospheric oxygen and carbon dioxide at somewhat stable levels.

Cellular respiration doesn't happen all at once, however. Glucose is broken down slowly so that cells convert as much sugar as possible into the usable form of energy, ATP. Still, some energy is lost in the process in the form of heat. When one molecule of glucose is broken down, it can be converted to a net total of 36 or 38 molecules of ATP. Although the process is not 100% efficient, it is much more efficient than, for instance, a car engine obtaining energy from gasoline.

Cellular respiration can be divided into three phases.

1. Glycolysis: the breakdown of glucose.
2. The Kreb Cycle (citric acid cycle): the formation of electron carriers.
3. The electron transport chain (Oxidative Phosphorylation): the formation of ATP.

In eukaryotic cells, the first phase takes place in the cytoplasm of the cell, while the other phases are carried out in the mitochondria. This organelle is known as the "powerhouse" of the cell because this is the organelle where the ATP that powers the cell is produced.

Glycolysis

The first step of cellular respiration is glycolysis. During **glycolysis,** the 6-carbon glucose is practically "cut in half," broken down into two 3-carbon pyruvate molecules. Glycolysis requires an initial energy-investment step, although in the end, glycolysis produces more energy than was initially invested. Two ATP molecules are used to convert glucose into the two 3-carbon pyruvate molecules. These 3-carbon molecules are then oxidized, which means that they lose electrons, as electrons are transferred to the high energy electron acceptor NAD^+, producing the electron carrier NADH. This oxidation step helps produce 4 ATP molecules from ADP. That means, taking into account the initial investment of 2 ATP molecules, glycolysis has a net production of 2 ATP.

TABLE 5.2: An Overview of Glycolysis

Inputs	Outputs Net Outputs
Glucose (6-carbon molecule)	2 pyruvate (3-carbon molecule)
2 NAD^+	2 NADH (electron carrier)
2 ATP (energy)	2 ADP
4 ADP	4 ATP (energy)

Fill in the NET products of Glycolysis in the table.

After glycolysis, the pyruvate can go down several different paths. If there is oxygen available, the pyruvate moves inside the mitochondrion to produce more ATP during further break-down stages. In the absence of oxygen, the fermentation process begins.

Inside the Mitochondria

If oxygen is available, the next step of cellular respiration is moving the pyruvate into the mitochondria. The mitochondria have a double membrane. The inner membrane is known as the **cristae**, and is folded to form many internal layers. Some steps of cellular respiration occur in the cristae, while others take place in the **matrix**, the inner compartment of the mitochondrion that is filled with enzymes in a gel-like fluid.

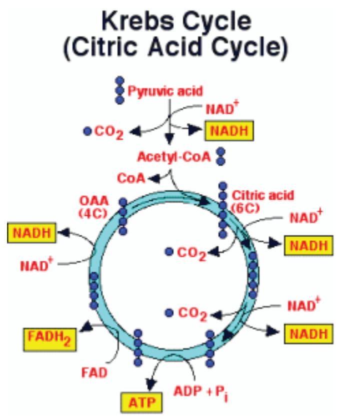


FIGURE 5.7
the Kreb cycle starts with pyruvic acid (pyruvate) and produces energy. What are the final products of the Kreb cycle?

Within the mitochondria the **Kreb's Cycle** or **citric acid cycle** occurs. The citric acid cycle is a series of oxidation steps that produce NADH and $FADH_2$, another type of electron carrier. These electron carriers will be used in the final step of cellular respiration. To begin the Kreb's Cycle, the 3-carbon pyruvate from glycolysis must be converted into a 2-carbon molecule, which then can enter the cycle. During the cycle carbon dioxide is produced. Two molecules of ATP are also produced per each initial glucose molecule.

In the final steps of cellular respiration, the **electron transport chain** accepts the electrons from glucose that are being carried by NADH and $FADH_2$. These electrons are passed along the chain until they are finally combined with oxygen, which with the addition of hydrogen ions, becomes water. That is the key reason why this process only occurs in the presence of oxygen. Illustrated in **Figure** below.

As the electrons move down the electron transport chain, energy is released and later used to synthesize ATP. The process of ATP synthesis is exactly the same as photosynthesis; hydrogen ions are pumped across the cristae of the mitochondria, forming a chemiosmotic gradient, and ATP synthase uses the energy of the movement of hydrogen ions back across the membrane, from high to low concentration, to make ATP.

Because oxygen is the final electron acceptor in this process, the electron transport chain can only occur in the presence of oxygen. This is known as **aerobic** respiration. However, there is not always enough oxygen present for aerobic respiration to occur. In this case, the next step after glycolysis will be fermentation instead of the citric acid cycle.

Fill in the NET products of the Citric Acid Cycle in the table.

TABLE 5.3: **An Overview of the Citric Acid Cycle**

Inputs	Outputs Net Outputs
2 two-carbon molecules	4 CO_2
6 NAD^+	6 NADH (electron carrier)
2 FAD^+	2 $FADH_2$ (electron carrier)
2 ADP	2 ATP (energy)

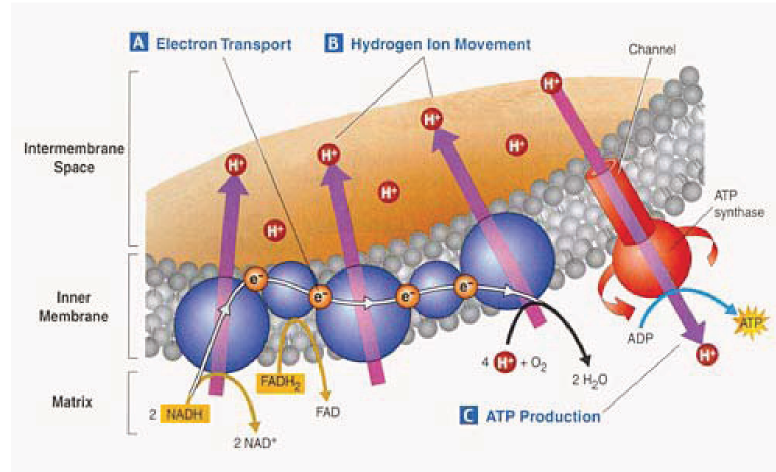


FIGURE 5.8
the Electron Transport Chain takes place in the Mitochondria and changes NADH and FADH in to ATP. What is the final product of the ETC?

TABLE 5.4: **An Overview of the Electron Transport Chain**

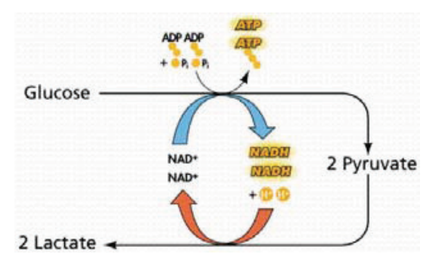
Inputs	Outputs	Net Outputs
6 O_2	6 H_2O	
8 NADH	8 NAD^+	
2 $FADH_2$	2 FAD^+	
32-34 ADP	32-34 ATP	

Fermentation

Sometimes cellular respiration is **anaerobic**, occurring in the absence of oxygen. In the process of **fermentation,** the NAD^+ is recycled so that is can be reused in the glycolysis process. No additional ATP is produced during fermentation, so the organism only obtains the two net ATP molecules per glucose from glycolysis.

Yeasts (single-celled eukaryotic organisms) carry on **alcoholic fermentation** in the absence of oxygen, making ethyl alcohol (drinking alcohol) and carbon dioxide. Alcoholic fermentation is central to bread baking. The carbon dioxide bubbles allow the bread to rise, and the alcohol evaporates. In wine making, the sugars of grapes are fermented to produce the wine.

Animals and some bacteria and fungi carry out **lactic acid fermentation.** Lactate (lactic acid) is a waste product of this process. Our muscles undergo lactic acid fermentation during strenuous exercise, when oxygen cannot be delivered to the muscles quickly enough. The buildup of lactate is what makes your muscles sore after vigorous exercise. Bacteria that produce lactate are used to make cheese and yogurt (**Figure** 4.8). Tooth decay is also accelerated by lactate from the bacteria that use the sugars in your mouth. In all these types of fermentation, the goal is the same: to recycle NAD^+ for glycolysis.



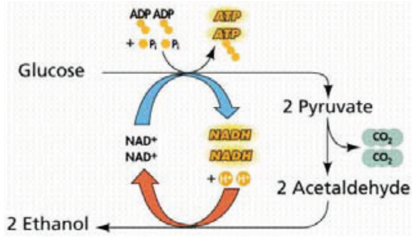


FIGURE 5.9
Products of fermentation include cheese (lactic acid fermentation) and wine (alcoholic fermentation).

Lesson Summary

- Cellular respiration is the breakdown of glucose to release energy in the form of ATP.
- Glycolysis, the conversion of glucose into two 3-carbon pyruvate molecules, is the first step of cellular respiration.
- If oxygen is available, the pyruvate enters the mitochondria and goes through a series of reactions, including the citric acid cycle, to produce more ATP.
- If oxygen is not available, the pyruvate is reduced during the process of fermentation to free up more NAD^+ for glycolysis, and there is no net gain of ATP.

Review Questions

1. What are the products of alcoholic fermentation?
2. What is the metabolic process where glucose is ultimately converted to two molecules of pyruvate?
3. Why do your muscles get sore after vigorous exercise?
4. What is the purpose of fermentation?
5. Where does the citric acid cycle take place?
6. Write the chemical reaction for the overall process of cellular respiration.
7. Which is more efficient, aerobic or anaerobic cellular respiration?

Points to Consider

- Now that we know how the cell gets its energy, we are going to turn our attention to cell division. Cell division is a highly regulated process.
- What do you think could happen if your cells divide uncontrollably?
- When new life is formed, do you think it receives all the DNA of the mother and the father?
- Why do you think you might need new cells throughout your life?

Vocabulary that Students need to Learn:

ATP

Chlorophyll

Photosynthesis

Cellular Respiration

Homeostasis

Fermentation

Anaerobic respiration

Aerobic respiration

5.4 References

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CHAPTER 6 Cell Growth, Division and Reproduction - Edited

Chapter Outline

6.1 The Cell Cycle and Mitosis (Asexual Reproduction)

Lesson Objectives

- Describe the properties of cell division in prokaryotes.
- Describe cell division in eukaryotes. Explain the main differences between cell division in prokaryotic and eukaryotic cells.
- Describe the basic properties of chromosomes.
- Describe the key steps in the cell cycle.
- Identify and describe the main processes in mitosis.
- Describe how the cell cycle is controlled and define cancer.

Introduction

You are made of many different types of cells. Nerve cells, skin cells, muscle cells, and many more. These cells obviously have many different functions, yet they all develop from the first cell that makes you. So do they all have the same DNA? Are all the cells in your body genetically identical? How does the first cell of an organism know to become two cells, then four cells, and so on? What tells these cells what to do? Your body produces about 25 million genetically identical cells every second. These new cells are formed when older cells divide, a process called cell division or cell reproduction.

Cell division is the final step in the life of a cell, otherwise known as the cell cycle. Eukaryotic cells and prokaryotic cells complete this process by a number of different mechanisms. The cell cycle is a repeating series of events, during which the eukaryotic cell carries out its necessary functions, including metabolism, cellular growth, and division, resulting in two genetically identical daughter cells. To produce two genetically identical daughter cells, the chromosomes need to replicate and the nucleus and cytoplasm need to divide. These are key events in the life of a cell.

Cell Division in Prokaryotes

Prokaryotic organisms reproduce asexually by **binary fission**, a process that produces identical offspring (**Figure** 6.1). In asexual reproduction, a single parent produces genetically identical offspring. As prokaryotes do not have a nucleus, and have only one circular chromosome, they do not need to reproduce by the same mechanism as eukaryotic cells. Prokaryotic cell division is a much simpler process. In prokaryotic cell division, after the single chromosome is copied, the cell grows larger. Eventually the two chromosomes separate and move to opposite ends of the cell. Newly formed cell membrane then grows into the center of the cell, separating the two chromosomes, and forming two genetically identical daughter cells. The formation of two daughter cells is called cytokinesis.

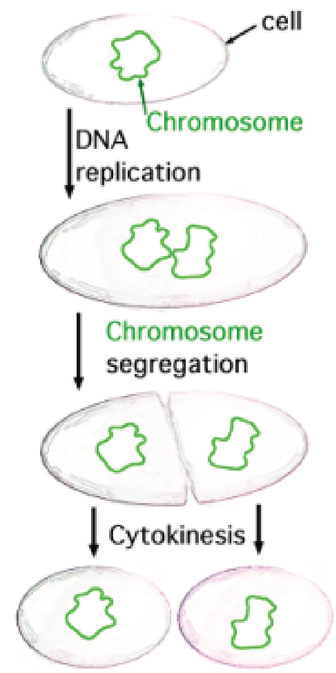


FIGURE 6.1
Binary fission. In binary fission, the single chromosome is copied and eventually separates into two separate chromosomes, the cell grows larger, and two identical cells form by cytokinesis.

Under ideal conditions, reproduction in bacteria is extremely efficient, with some bacteria reproducing every 20 minutes. This makes bacteria an extremely effective tool for the molecular biologist. However, bacteria do not usually live in ideal conditions; otherwise, bacteria would grow and divide extremely rapidly, eventually covering the surface of Earth. Bacterial growth is limited by nutrients and water, predation, and by their own wastes.

Cell Division in Eukaryotes

Cell division in eukaryotic organisms is very different from that in prokaryotes, mainly because of the many chromosomes in the nuclei of eukaryotic cells. Cell division in eukaryotic organisms is necessary for development, growth, and repair, which is called **mitosis**. This cell division ensures that each resulting daughter cell receives a complete copy of the organism's entire genome. Remember that all of an organism's DNA must be present in each somatic, or body, cell. This DNA contains the information necessary for that cell to perform its functions, and to give that organism its traits. Therefore, prior to cell division, the eukaryotic cell's complete genome must be copied, ensuring that each daughter cell receives a complete set of the genome.

The second type of cell division is the formation of **gametes**, an organism's reproductive cells, such as sperm and egg cells, this type of cell division is called **meiosis**. This cell division ensures that each gamete receives half the amount of an organism's DNA.

DNA, Chromosomes, and Genes

DNA contains the information necessary to make proteins, direct a cell's activities, and give an organism its traits contolled by the **genes**. A gene contains the information necessary to encode an RNA molecule or a protein. A single DNA molecule contains hundreds to thousands of genes.

Prior to cell division, the DNA must duplicate itself in a process called DNA replication. This ensures that each resulting cell receives a complete set of the organism's genome. But how is the replicated DNA divided up evenly? What guarantees that each new cell will receive a complete set of DNA? It was the identification of chromosomes that allowed this process to be characterized. As a eukaryotic cell prepares to divide, the DNA and associated proteins (histones) coil into a structure, known as a **chromosome** (**Figure** 6.2). The DNA copies itself prior to this

process, so the chromosome that forms consists of two identical chromatids, known as **sister chromatids**, identical copies of DNA. The two chromatids are attached at a region called the **centromere.** The chromatids separate from each other when the nucleus divides just prior to cell division. Thus, each new cell that results after cell division will have the complete amount of genetic material, identical to the original, or parent, cell. In human cells, this amounts to 46 chromosomes. These chromosomes come in pairs (one from each pair inherited from each parent). So these 46 chromosomes are actually two sets of 23 chromosomes each.

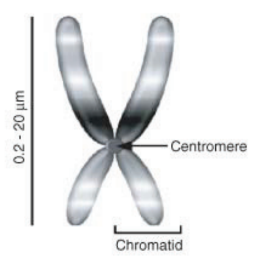


FIGURE 6.2
A representation of a condensed eukaryotic chromosome, as seen after the DNA has been copied. The chromosome is made of two identical, or sister, chromatids held together by a centromere.

Each human **somatic cell** (a body cell, or every cell other than a gamete (reproductive cell)) normally has two sets of chromosomes, one set inherited from each parent. Each set contains 23 chromosomes, for a total of 46 chromosomes. Each chromosome differs in size, from over 250 million nucleotide pairs to less than 50 million nucleotide pairs. Each chromosome contains a specific set of genes, making each chromosome essential to survival.

Each pair of chromosomes consists of two chromosomes that are similar in size, shape, and genes. These pairs of chromosomes are known as **homologous chromosomes**, or **homologues**. Upon fertilization, a **zygote** is formed (**Figure** 6.3). A zygote is the first cell of a new individual. In humans, a zygote contains 23 pairs (or two sets) of chromosomes. Any cell containing two sets of chromosomes is said to be **diploid**. The zygote forms from the fusion of two **haploid** gametes. A haploid cell contains one set of chromosomes. In humans, a haploid gamete contains 23 chromosomes. Biologists use the symbol n to represent one set of chromosomes (haploid), and $2n$ to represent two sets (diploid). In humans, each set of chromosomes contains 22 **autosomes** and 1 sex chromosome. Autosomes are chromosomes that are not directly involved in determining the sex of an individual. The sex chromosomes contain genes that determine the sex of an individual.

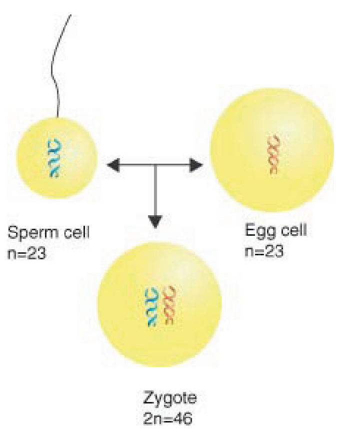


FIGURE 6.3
Upon fertilization a diploid zygote is formed. In humans, a zygote has 46 chromosomes, 23 inherited from each parent. The gametes, sperm and eggs, are haploid cells, with 23 chromosomes each.

Whereas autosomes are found as homologous pairs in somatic cells, sex chromosomes come in two different sizes, shapes, and contain different genes. In many organisms, including humans, the sex chromosomes are known as the X and Y chromosomes. The Y chromosome contains genes that cause male development. Therefore, any individual with a Y chromosome is male, and a male will have both an X and Y chromosome (XY). Females, without a Y

chromosome, will have two X chromosomes (XX). As females have two X chromosomes, they must pass an X chromosome to all of their children. As males have both an X chromosome (inherited from their mother) and a Y chromosome, they can give either chromosome to their children. If a child inherits a Y from his father, he will be male; if a child inherits an X from her father, she will be female. It therefore is the male gamete that determines the sex of the offspring.

The Cell Cycle

Cell division in eukaryotic cells is much more complex than in prokaryotic cells because of the many chromosomes within the nucleus. Both the cytoplasm and the genetic material must be divided, ensuring that each resulting daughter cell receives 46 separate chromosomes. To ensure this, in addition to the cell performing its necessary functions, the DNA must be copied, as must many organelles, prior to cell division.

The life of a eukaryotic cell is a cycle, known as the **cell cycle** (**Figure** 6.4). The cell cycle is a repeating series of cellular growth and division. The cell cycle has five phases: the first growth (G_1) phase, the synthesis (S) phase, the second growth (G_2) phase, mitosis, and cytokinesis, though many consider mitosis and cytokinesis to be combined into one phase. The cell spends the majority of the cycle in the first three phases of the cycle, collectively known as **interphase**. After cytokinesis, two genetically identical daughter cells are formed.

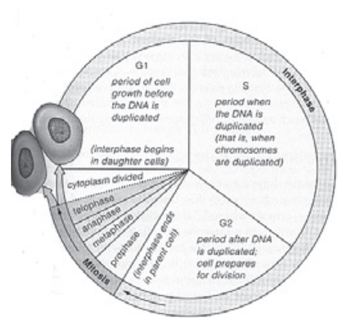


FIGURE 6.4
The Cell Cycle. The cell cycle depicts the life of an eukaryotic cell. The cell cycle has five phases.

The first phase is known as (G_1) growth phase: The cell spends most of its life in the G_1 phase. During this phase, a cell undergoes rapid growth and the cell performs its routine functions. If a cell is not dividing, the cell remains in this phase.

The second phase is (S) synthesis phase: For two genetically identical daughter cells to be formed, the cell's DNA must be copied or replicated.

The third phase is (G_2) second growth phase is a shortened growth period in which many organelles are reproduced or manufactured. Parts necessary for cell division are made during G_2.

The fourth phase is **Mitosis,** the phase of nuclear division, in which one nucleus divides and becomes two nuclei. The final phase is **cytokinesis**, in which the cytoplasm divides in half, producing two daughter cells, each containing a complete set of genetic material, DNA.

Interphase

Most of the cell cycle consists of **interphase,** the time between cell divisions. During this time the cell carries out its normal functions and prepares for the next stage. Interphase can be divided into three stages: the first growth phase (G1), the synthesis phase (S), and the second growth phase (G2). During the G1 stage, the cell doubles in size and doubles the number of organelles. Next, during the S stage, the DNA is replicated. In other words, an identical copy of all the cell's DNA is made. This ensures that each new cell that results after cell division has a set of genetic

material identical to that of the parental cell. Finally, in the G2 stage proteins are synthesized that will aid in cell division. In the end of interphase, the cell is ready to enter mitosis.

Mitosis

Mitosis is the division of the cell's nucleus, the final step before two daughter cells are produced. The cell enters mitosis as it approaches its size limitations. Four distinct phases of mitosis have been recognized: *prophase, metaphase, anaphase, and telophase,* with each phase merging into the next one (**Figure** 6.5).

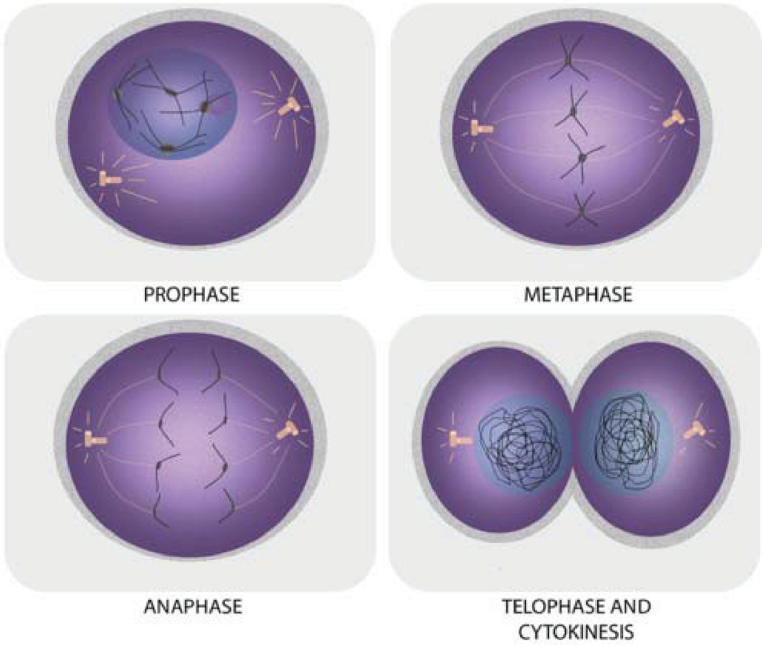


FIGURE 6.5
During mitosis, the nucleus divides, paving the way for two cells to be produced after cell division, each with a complete makeup of genetic material.

Prophase is the first and longest phase of mitosis. During prophase, the DNA coils up into visible chromosomes, each made up of two sister chromatids held together by the centromere. The nucleus disappears as the nuclear envelope and nucleolus break apart. The centrioles begin to move to opposite ends, or poles, of the cell. As the centrioles migrate, the fiber-like spindle begins to elongate between the centrioles. The spindle is a thin, cage-like structure made out of microtubules. In plant cells, the spindle forms without centrioles. The spindle plays an essential role moving chromosomes and in the separation of sister chromatids.

During **metaphase** the spindle attaches to the centromere of each chromosome. Helped by the spindle, the chromosomes line up at the middle, or equator, of the cell, also known as the metaphase plate. Each sister chromatid is attached to a separate spindle fiber, with one fiber extending to one pole, and the other fiber extending to the other pole. This ensures that the sister chromatids separate and end up in distinct cells after cell division.

Anaphase is the phase in which the sister chromatids separate. The sister chromatids are pulled apart by the shortening of the microtubules of the spindles, similar to the reeling in of a fish by the shortening of the fishing line. One sister chromatid moves to one pole of the cell, and the other sister chromatid moves to the opposite pole. At the end of anaphase, each pole of the cell has a complete set of chromosomes, identical to the amount of DNA at the beginning of G_1 of the cell cycle.

Telophase is essentially the opposite of prophase. The chromosomes begin to unwind in preparation to direct the cell's metabolic activities. The spindle begins to break down, allowing a new nucleus to form. This is followed by **cytokinesis**, the division of the cytoplasm, resulting in two genetically identical cells, ready to enter G_1 of the next cell cycle. The phases of mitosis are shown in **Figure** 6.6.

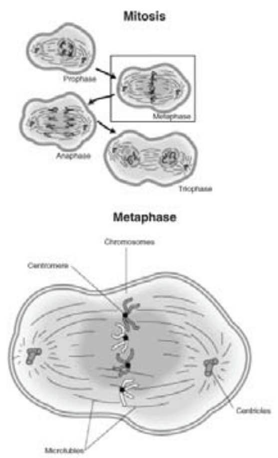
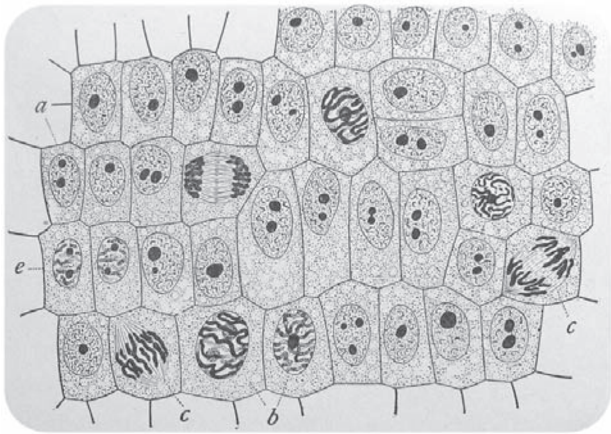


FIGURE 6.6
Mitosis. The phases of mitosis are depicted. The second phase, metaphase, is shown with the chromosomes lined up at the equator of the cell and the microtubule spindle fibers extending from the centrioles to the centromeres of the chromosomes.

Cytokinesis differs between plant and animal cells. In animal cells, the plasma membrane pinches inward along the cell's equator until two cells are formed. In plant cells, a cell plate forms along the cells equator. A new membrane grows along each side of the cell plate, with a new cell wall forming on the outside of each new membrane.



This is a picture of dividing plant cells. Cell division in plant cells differs slightly from animal cells as a cell wall must form. Note that most of the cells are in interphase. Can you find examples of the different stages of mitosis?

Control of the Cell Cycle

How does the cell know when to divide? How does the cell know when to replicate the DNA? The answers to these questions have to do with the control of the cell cycle. But how is the cell cycle controlled?

The cell cycle is controlled by a number of protein-controlled feedback processes. Two types of proteins involved in the control of the cell cycle are kinases and cyclins. Cyclins activate kinases. Cyclins are a group of proteins that is rapidly produced at key stages in the cell cycle. Kinases activate other target molecules. It is this precise regulation of proteins that triggers advancement through the cell cycle.

The cell cycle has key checkpoints. When the cell receives key signals or information (feedback regulation), the cell can begin the next phase of the cell cycle. The cell can also receive signals that delay passage to the next phase of the cell cycle. These signals allow the cell to complete the previous phase before moving forward. Three key checkpoints are the cell growth (G_1) checkpoint, the DNA synthesis (G_2) checkpoint, and the mitosis checkpoint.

The cell growth (G_1) checkpoint allows the cell to proceed into the S phase of the cell cycle and continue on to divide. The cell spends most of the cycle in the G_1 phase. G_1 is where the cell carries out its main functions. If the

cell has performed its functions and has grown to significant size to be divided in half, key proteins will stimulate DNA replication to begin. If the cells are not to divide, such as some muscle and nerve cells, the cell will stop at this checkpoint and move into a resting phase. Some cells may stay in this resting period permanently, never dividing.

The DNA synthesis (G_2) checkpoint determines if the cell is ready for mitosis. DNA repair enzymes check the replicated DNA at this point. If the checkpoint is passed, the many molecular mechanisms and processes needed for mitosis will begin.

The mitosis checkpoint determines the end of one cycle and the beginning of the next. This checkpoint signals the end of mitosis, allowing the cell to prepare for the beginning of G_1 of the next cell cycle.

Cancer and the Cell Cycle

Many cancers result from uncontrolled cell division, when the regulation of the cycle is lost (**Figure** 6.9). Cancerous cells divide much more rapidly than healthy cells. These cells use the blood and nutrients that other cells need and they can stress the environment of the healthy cells. As cancerous cells do not provide any useful function to the organism, they are extremely harmful. If cancerous cells are allowed to grow uncontrolled, they will kill the host organism. Many cancerous cells are the products of normal cells that have lost the ability to regulate the cell cycle. The genes that encode the proteins involved in cell cycle regulation have mutations. One category of genes, called oncogenes, accelerate the cell cycle. Many cancers can be inherited, such as breast cancer. Others are triggered by an environmental stimulus, such as through the relationship between tobacco smoke and lung cancer, or ultraviolet radiation and skin cancer.

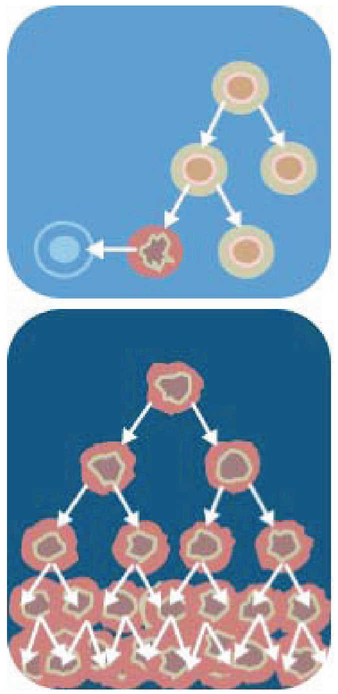


FIGURE 6.7

When normal cells are damaged beyond repair, they are eliminated. (A) diagrams damaged cells being destroyed. Cancer cells avoid elimination and, because of uncontrolled cell division, continue to multiply in an unregulated manner. (B) depicts damaged cells dividing in an uncontrolled fashion.

Lesson Summary

- The cell cycle is a repeating series of events, characterizing the life of a eukaryotic cell.
- Binary fission is a form of cell division in prokaryotic organisms that produces identical offspring.

- As a eukaryotic cell prepares to divide, the DNA and associated proteins coil into a structure, known as a chromosome.
- The DNA copies during the S phase of the cell cycle, resulting in a chromosome that consists of two identical chromatids, known as sister chromatids, attached at a region called the centromere.
- Any cell containing two sets of chromosomes is said to be diploid; the zygote forms from the fusion of two haploid gametes.
- The cell cycle has five phases: the first growth (G_1) phase, the synthesis (S) phase, the second growth (G_2) phase, mitosis, and cytokinesis.
- Mitosis is the division of the nucleus; four distinct phases of mitosis have been recognized: prophase, metaphase, anaphase, and telophase.
- Cytokinesis is the division of the cytoplasm.
- The cell cycle is controlled through feedback mechanisms.
- Cancer results from uncontrolled cell division, due to the loss of regulation of the cell cycle.

Review Questions

1. How does cell division in bacteria differ from mitosis in eukaryotes?
2. Describe the structure of a chromosome in prophase of mitosis.
3. What is cytokinesis and when does it occur?
4. What is a centromere?
5. Describe interphase.
6. Describe the main steps of mitosis.
7. What is binary fission?
8. What is the difference between plant and animal cell division?

Points to Consider

- A human cell has 46 chromosomes, while a bacterial cell has only one chromosome. Would you think that the number of chromosomes relates to the complexity of the cell or organism?
- Mitosis and cytokinesis produce two genetically identical daughter cells. Think about how a cell with half as much DNA, such as a sex cell, may form.
- As not every species has members of the opposite sex, such as bacteria, yet all organisms must reproduce to stay alive, think about how these sexless organisms may reproduce.

6.2 Meiosis (Sexual Reproduction)

Lesson Objectives

- Describe asexual reproduction; explain the genetic relationship between parent and offspring.
- Describe sexual reproduction; explain the genetic relationship between parent and offspring.
- Identify and describe the main steps of meiosis, distinguishing between the quantity of genetic material in the parent and resulting cells.
- Describe gametogenesis and identify the key differences between oogenesis and spermatogenesis.
- Distinguish between the three types of sexual life cycles.

Introduction

Some organisms look and act exactly like their parent. Others share many similar traits, but they are definitely unique individuals. Some species have two parents, whereas others have just one. How an organism reproduces determines the amount of similarity the organism will have to its parent. Asexual reproduction produces an identical individual, whereas sexual reproduction produces a similar, but unique, individual. In sexual reproduction, meiosis produces haploid gametes that fuse during fertilization to produce a diploid zygote (**Figure** 6.10 and **Figure** 6.3).

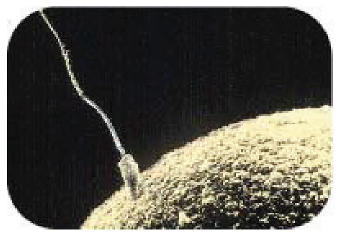


FIGURE 6.8
Fertilization of an egg cell by a sperm cell. In sexual reproduction, haploid gametes fuse to produce a diploid zygote.

Asexual Reproduction

Are there male and female bacteria? How could you tell? Remember, bacteria have just one chromosome; they do not have an X or Y chromosome. So they probably have a very simplified form of reproduction. Asexual reproduction, the simplest and most primitive method of reproduction, produces a **clone**, an organism that is genetically identical to its parent. Haploid gametes are not involved in asexual reproduction. A parent passes all of its genetic material to the next generation. All prokaryotic and many eukaryotic organisms reproduce asexually.

There are a number of types of asexual reproduction including fission, fragmentation and budding. In fission, a parent separates into two or more individuals of about equal size. In fragmentation, the body breaks into several fragments, which later develop into complete adults. In budding, new individuals split off from existing ones. Eukaryotic organisms, such as the single cell yeast and multicellular hydra, undergo budding (**Figure** 6.11).

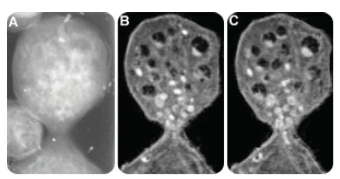


FIGURE 6.9
Magnification of a budding yeast.

Sexual Reproduction and Meiosis

Why do you look similar to your parents, but not identical? First, it is because you have two parents. Second, it is because of sexual reproduction.

Whereas asexual reproduction produces genetically identical clones, sexual reproduction produces genetically diverse individuals. As both parents contribute half of the new organism's genetic material, the offspring will have traits of both parents, but will not be exactly like either parent.

Organisms that reproduce sexually by joining gametes, a process known as fertilization, must have a mechanism to produce haploid gametes. This mechanism is meiosis, a type of cell division that halves the number of chromosomes. During meiosis the pairs of chromosomes separate and segregate randomly to produce gametes with one chromosome from each pair. Meiosis involves two nuclear and cell divisions without an interphase in between, starting with one diploid cell and generating four haploid cells (**Figure** 6.12). Each division, named meiosis I and meiosis II, has four stages: prophase, metaphase, anaphase, and telophase. These stages are similar to those of mitosis, but there are distinct and important differences.

Prior to meiosis, the cell's DNA is replicated, generating chromosomes with two sister chromatids. A human cell prior to meiosis will have 46 chromosomes, 22 pairs of homologous autosomes, and 1 pair of sex chromosomes. Homologous chromosomes are similar in size, shape, and genetic content. You inherit one chromosome of each pair from your mother and the other one from your father.

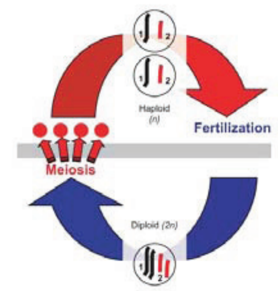


FIGURE 6.10
During meiosis the number of chromosomes is reduced from a diploid number (2n) to a haploid number (n). During fertilization, haploid gametes come together to form a diploid zygote and the original number of chromosomes (2n) is restored.

The stages of meiosisI and meiosis II are summarized below. The stages will be described for a human cell, starting with 46 chromosomes.

Prophase I: prophase I is very similar to prophase of mitosis, but with one very significant difference. In Prophase I, the nuclear envelope breaks down, the chromosomes condense, and the centrioles begin to migrate to opposite poles of the cell, with the spindle fibers growing between them. During this time, the homologous chromosomes form pairs. These homologous chromosomes line up gene-for-gene down their entire length, allowing crossing-over to occur. This is an important step in creating genetic variation and will be discussed later.

Metaphase I: In metaphase I, the 23 pairs of homologous chromosomes line up along the equator of the cell. During mitosis, 46 individual chromosomes line up during metaphase. Some chromosomes inherited from the father are facing one side of the cell, and some are facing the other side.

Anaphase I: During anaphase I the spindle fibers shorten, and the homologous chromosome pairs are separated from each other. One chromosome from each pair moves toward one pole, with the other moving toward the other pole, resulting in a cell with 23 chromosomes at one pole and the other 23 at the other pole. The sister chromatids remain attached at the centromere. Because human cells have 23 pairs of chromosomes, this independent assortment of chromosomes produces 2^{23}, or 8,388,608 possible configurations. More on independent assortment of chromosomes will be presented in the chapter on Mendelian Genetics.

Telophase I: The spindle fiber disassembles and the nucleus reforms. This is quickly followed by cytokinesis and the formation of two haploid cells, each with a unique combination of chromosomes, some from the father and the

rest from the mother. After cytokinesis, both cells immediately enter meiosis II; the DNA is not copied in between. Meiosis II is essentially the same as mitosis, separating the sister chromatids from each other.

Prophase II: Once again the nucleus breaks down, and the spindle begins to reform as the centrioles move to opposite sides of the cell.

Metaphase II: The spindle fibers align the 23 chromosomes, each made out of two sister chromatids, along the equator of the cell.

Anaphase II: The sister chromatids are separated and move to opposite poles of the cell. As the chromatids separate, each is known as a chromosome. Anaphase II results in a cell with 23 chromosomes at each end of the cell; each chromosome contains half as much genetic material as at the start of anaphase II.

Telophase II: The nucleus reforms and the spindle fibers break down. Each cell undergoes cytokinesis, producing four haploid cells, each with a unique combination of genes and chromosomes.

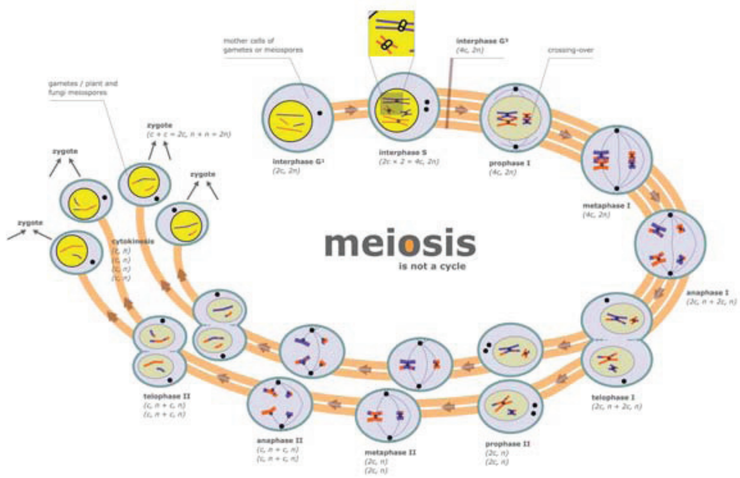


FIGURE 6.11

Meiosis is a process in which a diploid cell divides itself into four haploid cells.

- An excellent animation depicting meiosis can be viewed at

  http://www.youtube.com/watch?v=D1_-mQS_FZ0&feature=related.

Meiosis and Genetic Variation

Sexual reproduction results in infinite possibilities of genetic variation. This occurs through a number of mechanisms, including crossing-over, the independent assortment of chromosomes during anaphase I, and random fertilization.

Crossing-over occurs during prophase I. Crossing-over is the exchange of genetic material between non-sister chromatids of homologous chromosomes. Recall during prophase I, homologous chromosomes line up in pairs, gene-for-gene down their entire length, forming a configuration with four chromatids, known as a **tetrad**. At this point, the chromatids are very close to each other and some material from two chromatids switch chromosomes, that is, the material breaks off and reattaches at the same position on the homologous chromosome (**Figure** below). This exchange of genetic material can happen many times within the same pair of homologous chromosomes, creating unique combinations of genes. This process is also known as **recombination**.

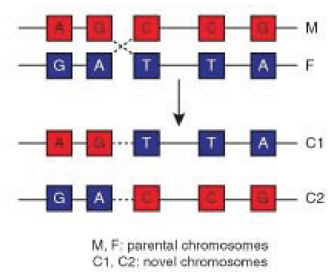


FIGURE 6.12

Crossing-over. A maternal strand of DNA is shown in red. Paternal strand of DNA is shown in blue. Crossing over produces two chromosomes that have not previously existed. The process of recombination involves the breakage and rejoining of parental chromosomes (M, F). This results in the generation of novel chromosomes (C1, C2) that share DNA from both parents.

As mentioned above, in humans there are over 8 million configurations in which the chromosomes can line up during metaphase I. It is the specific processes of meiosis, resulting in four unique haploid cells, that results in these many combinations. **Figure** below compares mitosis and meiosis. This independent assortment, in which the chromosome inherited from either the father or mother can sort into any gamete, produces the potential for tremendous genetic variation. Together with random fertilization, more possibilities for genetic variation exist between any two people than individuals alive today. Sexual reproduction is the random fertilization of a gamete from the female using a gamete from the male. In humans, over 8 million (2^{23}) chromosome combinations exist in the production of gametes in both the male and female. A sperm cell, with over 8 million chromosome combinations, fertilizes an egg cell, which also has over 8 million chromosome combinations. That is over 64 trillion unique combinations, not counting the unique combinations produced by crossing-over. In other words, each human couple could produce a child with over 64 trillion unique chromosome combinations.

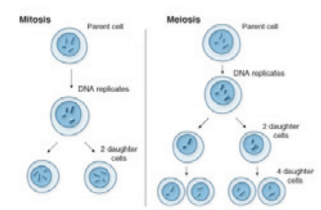


FIGURE 6.13

Mitosis vs. Meiosis Comparison. Mitosis produces two diploid daughter cells, genetically identical to the parent cell. Meiosis produces four haploid daughter cells, each genetically unique. See

Gametogenesis

At the end of meiosis, haploid cells are produced. These cells need to further develop into mature gametes capable of fertilization, a process called **gametogenesis** (**Figure** below). Gametogenesis differs between the sexes. In the male, the production of mature sperm cells, or **spermatogenesis**, results in four haploid gametes, whereas, in the female, the production of a mature egg cell, **oogenesis**, results in just one mature gamete.

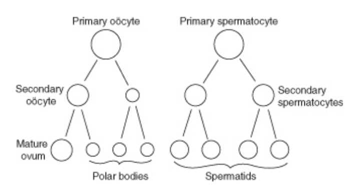


FIGURE 6.14

Analogies in the process of maturation of the ovum and the development of the spermatids. Four haploid spermatids form during meiosis from the primary spermatocyte, whereas only 1 mature ovum, or egg forms during meiosis from the primary oocyte. Three polar bodies may form during oogenesis. These polar bodies will not form mature gametes.

Sexual Life Cycles

Eukaryotes have three different versions of the sexual life cycle: a haploid life cycle, a diploid life cycle, and a life cycle known as the alternation of generations. A **life cycle** is the span in the life of an organism from one generation

to the next. All species that reproduce sexually follow a basic pattern, alternating between haploid and diploid chromosome numbers. The sexual life cycle depends on when meiosis occurs and the type of cell that undergoes meiosis.

Haploid Life Cycles

The haploid life cycle is the simplest life cycle. Organisms with this life cycle, such as many protists and some fungi and algae, spend the majority of their life cycle as a haploid cell. In fact, the zygote is the only diploid cell. The zygote immediately undergoes meiosis, producing four haploid cells, which grow into haploid multicellular organisms. These organisms produce gametes by mitosis. The gametes fuse through a process called fusion to produce diploid zygotes which undergo meiosis, continuing the life cycle.

Diploid Life Cycles

Organisms that have a diploid life cycle spend the majority of their lives as diploid adults. All diploid adults inherit half of their DNA from each parent. When they are ready to reproduce, diploid reproductive cells undergo meiosis and produce haploid gametes. These gametes then fuse through fertilization and produce a diploid zygote, which immediately enters G_1 of the cell cycle. Next, the zygote's DNA is replicated. Finally, the processes of mitosis and cytokinesis produce two genetically identical diploid cells. Through repeated rounds of growth and division, this organism becomes a diploid adult and the cycle continues.

Alternation of Generations

Plants, algae, and some protists have a life cycle that alternates between diploid and haploid phases, known as alternation of generations. In plants, the life cycle alternates between the diploid sporophyte and haploid gametophyte. Spore forming cells in the diploid sporophyte undergo meiosis to produce **spores**, a haploid reproductive cell. Spores can develop into an adult without fusing with another cell. The spores give rise to a multicellular haploid gametophyte, which produce gametes by mitosis. The gametes fuse, producing a diploid zygote, which grow into the diploid sporophyte.

Lesson Summary

- Asexual reproduction produces a clone, an organism that is genetically identical to its parent.
- Asexual reproduction includes fission, fragmentation and budding.
- Sexual reproduction involves haploid gametes and produces a diploid zygote through fertilization.
- Meiosis is a type of cell division that halves the number of chromosomes. There are eight stages of meiosis, divided into meiosis I and meiosis II. DNA is not replicated between meiosis I and meiosis II.
- Crossing-over, the independent assortment of chromosomes during anaphase I, and random fertilization result in genetic variation.
- Meiosis is a step during spermatogenesis and oogenesis. Spermatogenesis produces four haploid sperm cells, while oogenesis produces one mature ovum.
- Eukaryotes have three different versions of the sexual life cycle: a haploid life cycle, a diploid life cycle, and a life cycle known as the alternation of generations. The sexual life cycle depends on when meiosis occurs and the type of cell that undergoes meiosis.

Review Questions

1. Define crossing-over in meiosis.

2. Describe how crossing-over, independent assortment, and random fertilization lead to genetic variation.
3. Compare and contrast mitosis and meiosis.
4. List the main differences between asexual and sexual reproduction.
5. How many chromosomes does a diploid human cell have? How many chromosomes does a haploid human cell have?
6. Name the three different sexual life cycles. What characterizes the differences between these life cycles?

Vocabulary Students need to Learn:

Mitosis

Meiosis

Sexual Reproduction

Asexual Reproduction

Prokaryote

Eukaryote

Cell cycle

Cancer

Gametes

Gene

Allele

Cytokinesis

Points to Consider

- The next unit, Genetics, discusses the branch of biology that studies heredity. What is heredity?
- What role do you think meiosis plays in heredity?
- Describe what would happen if gametes were formed by mitosis.
- Human Genetics is an ever increasingly important field of medicine. Explain why this field of medicine is so important.

Chapter 7 The Father of Genetics - Edited

Chapter Outline

7.1 Mendel's Investigations

Lesson Objectives

- Identify how Mendel's study of science and math was important to his success in research.
- Distinguish between characteristics and traits.
- Explain how Mendel was able to control pollination of the pea plants.
- Identify the terms used to describe the three generations in Mendel's studies.
- Predict and interpret patterns of inheritance in sexually reproducing organisms.
- State one reason for carrying out a monohybrid cross.
- Identify the traits that appeared in Mendel's F_2 generation.
- Identify the actions of dominant alleles and recessive alleles for a trait.
- Explain the Law of Segregation.
- Explain the Law of Independent Assortment.
- Explain Mendel's results in relation to genes and chromosomes.
- Distinguish between genotype and phenotype.

Introduction

For thousands of years, humans have understood that characteristics such as eye color or flower color are passed from one generation to the next. The passing of characteristics from parent to offspring is called **heredity**. Humans have long been interested in understanding heredity. Many hereditary mechanisms were developed by scholars but were not properly tested or quantified. The scientific study of genetics did not begin until the late 19th century. In experiments with garden peas, Austrian monk Gregor Mendel described the patterns of inheritance.

Gregor Mendel: Teacher and Scientist

Gregor Johann Mendel was an Augustinian monk, a teacher, and a scientist (**Figure** 7.1). He is often called the "father of modern genetics" for his study of the inheritance of traits in pea plants. Mendel showed that the inheritance of traits follows particular laws, which were later named after him. The significance of Mendel's work was not recognized until the turn of the 20th century. The rediscovery of his work led the foundation for the era of modern **genetics**, the branch of biology that focuses on heredity in organisms.

Johann Mendel was born in 1822 and grew up on his parents' farm in an area of Austria that is now in the Czech Republic. He overcame financial hardship and ill health to excel in school. In 1843 he entered the Augustinian Abbey in Brünn (now Brno, Czech Republic.) Upon entering monastic life, he took the name Gregor. While at the monastery, Mendel also attended lectures on the growing of fruit and agriculture at the Brünn Philosophical Institute. In 1849 he accepted a teaching job, but a year later he failed the state teaching examination. One of his examiners recommended that he be sent to university for further studies. In 1851 he was sent to the University of Vienna to study natural science and mathematics. Mendel's time at Vienna was very important in his development as a scientist. His professors encouraged him to learn science through experimentation and to use mathematics to help explain observations of natural events. He returned to Brünn in 1854 as a natural history and physics teacher.

Mendel's Experiments

In 1853 and 1854, Mendal published two papers on crop damage by insects. However, he is best known for his later studies of the pea plant *Pisum sativum*. Mendel was inspired by both his professors at university and his colleagues

FIGURE 7.1
Gregor Johann Mendel

at the monastery to study variation in plants. He had carried out artificial fertilization on plants many times in order to grow a plant with a new color or seed shape. **Artificial fertilization** is the process of transferring pollen from the male part of the flower to the female part of another flower. Artificial fertilization is done in order to have seeds that will grow into plants that have a desired trait, such as yellow flowers.

During Mendel's time, the popular **blending inheritance** hypothesis stated that offspring were a "mix" of their parents. For example, if a pea plant had one short parent and one tall parent, that pea plant would be of medium height. It was believed that the offspring would then pass on heritable units, or factors, for medium sized offspring. (Today we know these heritable units are genes; however, Mendel did not know of the concept of a gene.) Mendel noted that plants in the monastery gardens sometimes gave rise to plants that were not exactly like the parent plants, nor were they a "mix" of the parents. He also noted that certain traits reappeared after "disappearing" in an earlier generation. Mendel was interested in finding out if there was a predictable pattern to the inheritance of traits. Between 1856 and 1863 he grew and tested about 29,000 pea plants in the monastery garden.

Mendel may have chosen to study peas because they are fast-growing plants that are available in different varieties. For example, one variety of pea plant has purple flowers, as shown in **Figure** 7.2, while another variety has white flowers.

FIGURE 7.2
the pea plant species that Mendel studied.

Mendel chose to study seven characteristics of pea plants. A **characteristic** is a heritable feature, such as flower color. Each characteristic Mendel chose to study occurred in two contrasting traits. A **trait** is a heritable variant of

a characteristic, such as purple or white flower color. Table 7.1 lists the seven characteristics Mendel studied, and their two contrasting traits.

TABLE 7.1: The Seven Characteristics Mendel Studied and Their Contrasting Traits

Flower Color	Flower Position on Stem	Stem Length	Pod Shape	Pod Color	Seed Shape	Seed Color
violet-red (purple)	axial	tall	inflated	green	round	green
white	terminal	short	constricted	yellow	wrinkled	yellow

Pea Plant Pollination

In order to study these characteristics, Mendel needed to control the pollination of the pea plants. Pollination occurs when the pollen from the male reproductive part of a flower, called the anthers, is transferred to the female reproductive part of a flower, called the stigma. Pea plants are **self-pollinating**, which means the pollen from a flower on a single plant transfers to the stigma of the same flower or another flower on the same plant. In order to avoid self-pollination, Mendel removed the anthers from the flowers on a plant. He then carefully transferred pollen from the anthers of another plant and dusted the pollen onto the stamen of the flowers that lacked anthers. This process caused cross-pollination. **Cross-pollination** occurs when pollen from one flower pollinates a flower on a different plant. In this way, Mendel controlled the characteristics that were passed onto the offspring. **Figure** 7.3 shows the location of the male and female parts of *P. sativum*.

FIGURE 7.3
The location of the anthers in the pea flower. The anthers are illustrated alone in the image to the left of the transected flower (at right). Mendel controlled pollination of the plants by removing the immature anthers of certain plants.

Mendel's First Experiment

Mendel began his studies by growing plants that were true-breeding for a particular trait. A **true-breeding** plant will always produce offspring with that trait when they self-pollinate. For example, a true-breeding plant with yellow seeds will always have offspring that have yellow seeds. In his first experiment, Mendel cross-pollinated two true-breeding plants of contrasting traits, such as purple and white flowered plants. The true-breeding parent plants are referred to as the **P generation** (parental generation). The hybrid offspring of the P generation are called the **F_1 generation** (filial generation). The hybrid offspring of the F_1 generation are called the F_2 generation (filial generation).

Monohybrid Crosses

Mendel first worked with plants that differed in a single characteristic, such as flower color. A hybridization is a cross between two individuals that have different traits. A hybridization in which only one characteristic is examined is called a **monohybrid cross**. The offspring of such a cross are called **monohybrids**. Mendel noted that hybridizing true-breeding (P-generation) plants gave rise to an F_1 generation that showed only one trait of a characteristic. For example, a true-breeding purple-flowering plant crossed with a true-breeding white-flowering plant always gave rise to purple-flowered hybrid plants. There were no white-flowered hybrids! Mendel wanted to know what happened to the white-flowered plants' "heritable factors." If indeed the white-flower "heritable factor" had disappeared, all future offspring of the hybrids would be purple-flowered. To test this idea, Mendel let the F_1 generation plants self-pollinate and then planted the resulting seeds.

Mendel's Results

The F_2 generation plants that grew included white-flowered plants! Mendel noted the ratio of white flowered plants to purple-flowered plants was about 3:1. That is, for every three purple-flowered plants, there was one white flowered plant. **Figure** "The Three Generations of Mendel's Experiments" shows Mendel's results for the characteristic of flower color.

Mendel carried out identical studies over three generations, (P, F_1, and F_2), for the other six characteristics and found in each case that one trait "disappeared" in the F_1 generation, only to reappear in the F_2 generation. Mendel studied a large number of plants, as shown in **Table** 7.2"Results of F1 Generation Crosses for Seven Characteristics in P. sativum", so he was confident that the ratios of different traits in the F_2 generation were representative.

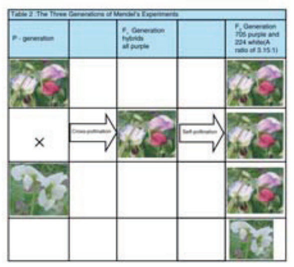


FIGURE 7.4

TABLE 7.2: Results of F1 Generation Crosses for Seven Characteristics in *P. sativum*

Characteristic	Dominant Trait	Recessive Trait	F2 Generation Dominant:Recessive	Ratio
Flower color	Purple	White	705:224	3.15:1
Flower position on stem	Axial	Terminal	651:207	3.14:1
Stem length	Tall	Short	787:277	2.84:1
Pod shape	Inflated	Constricted	882:299	2.95:1
Pod color	Green	Yellow	428:152	2.82:1
Seed shape	Round	Wrinkled or angular	5474:1850	2.96:1
Seed color	Yellow	Green	6022:2001	3.01:1

Mendel's Theory of Heredity

Based on his observations, Mendel developed four hypotheses. These hypotheses are known as Mendel's theory of heredity. The hypotheses explain a simple form of inheritance in which two alleles of a gene are inherited to result in one of several traits in offspring. In modern terms, these hypotheses are:

1. **There are different versions of genes**. These different versions account for variations in characteristics. Different versions of a gene are called **alleles.** For example, there is a "yellow-pod" allele and a "green pod" allele. The blending inheritance hypothesis was discredited by Mendel's allele hypothesis.
2. **When two different alleles are inherited together, one may be expressed, while the effect of the other may be "silenced."** In the case of pod color, the allele for green pods is always expressed and is **dominant**. The allele for yellow pods, which is not expressed, is **recessive**. For instance, if a plant inherits a "yellow-pod" gene and a "green pod" gene, it will have only green pods.
3. **For each characteristic, an organism inherits two alleles, one from each parent**. Mendel noted that offspring could inherit their traits from either parent. In the case of the expressed trait, it did not matter whether it was the male gamete or female gamete that supplied the gene.
4. **When gametes are formed, the two alleles of each gene are separated** (**Figure** below). During meiosis, each male or female gamete receives one allele for a trait. When the male and female gametes are fused at fertilization, the resulting zygote contains two alleles of each gene.

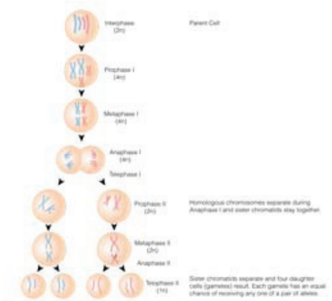


FIGURE 7.5

Alleles on homologous chromosomes are randomly separated during gamete formation. Upon fertilization, the fusion of a male and female gametes results in new combinations of alleles in the resulting zygote.

Random Segregation of Alleles

The **Law of Segregation** states that a pair of alleles is separated, or segregated, during the formation of gametes. During meiosis, homologous chromosomes are randomly separated. Each resulting gamete has an equal probability or chance of receiving either of the two alleles.

Mendel's Second Experiment

Mendel also crossed pea plants that differed in two characteristics, such as seed color and shape. A **dihybrid cross** is a cross in which the inheritance of two characteristics are tracked at the same time. The offspring of such a cross are called **dihybrids**. Mendel wanted to see if the inheritance of characteristics were dependent. He concluded that characteristics were inherited independently of each other.

The Law of Independent Assortment

The **Law of Independent Assortment**, also known as or Mendel's Second Law, states that the inheritance of one trait will not affect the inheritance of another. Mendel concluded that different traits are inherited independently of

each other, so that there is no relationship, for example, between seed color and seed shape. In modern terms, alleles of each gene separate independently during gamete formation.

Linked Genes on Chromosomes

We now know that the only alleles that are inherited independently are ones that are located far apart on a chromosome or that are on different chromosomes. There are many genes that are close together on a chromosome, and are packaged into the gametes together. Genes that are inherited in this way are called **linked genes**. Linked genes tend to be inherited together because they are located on the same chromosome. Genetic linkage was first discovered by the British geneticists William Bateson and Reginald Punnett shortly after Mendel's laws were rediscovered.

Mendelian Theory and Molecular Genetics

Mendel was perhaps lucky in that the characteristics he chose to study in the pea plants had a relatively simple pattern of inheritance. These characteristics were determined by one gene for which there were exactly two alleles. One of these alleles was dominant and the other recessive. Had any of these characteristics been determined by more than one gene, he may not have been able to develop such amazing insight into inheritance. In many instances, the relationship between genes and inheritance is more complex than that which Mendel found. Nevertheless, geneticists have since found that Mendel's findings can be applied to many organisms. For example, there are clear patterns of Mendelian inheritance in humans. Albinism (**Figure** 7.6), is a genetic disorder that is inherited as a simple Mendelian trait.

FIGURE 7.6
Albinism is a recessively inherited disorder in which the body does not produce enough of the pigment melanin. The skin, hair, and eyes of a person with albinism appear white or pale.

Dominant and Recessive Alleles

Mendel used letters to represent dominant and recessive factors. Likewise, geneticists now use letters to represent alleles. Capital letters refer to dominant alleles, and lowercase letters refer to recessive alleles. For example, the dominant allele for the trait of green pod color is indicated by G. The recessive trait of yellow pod color is indicated by g. A true-breeding plant for green pod color would have identical alleles GG in all its somatic cells. Likewise, a true-breeding plant for yellow pod color would have identical alleles gg in all of its somatic cells. During gamete formation, each gamete receives one copy of an allele. When fertilization occurs between these plants, the offspring receives two copies of the allele, one from each parent. In this case, all of the offspring would have two different alleles, Gg, one from each of its parents.

An organism that has an identical pair of alleles for a trait is called **homozygous**. The true-breeding parents GG and gg are homozygous for the pod color gene. Organisms that have two different alleles for a gene are called **heterozygous**. The offspring of the cross between the GG and gg plants are all heterozygous for the pod color gene. Due to dominance and recessiveness of alleles, an organism's traits do not always reveal its genetics. Therefore, geneticists distinguish between an organism's genetic makeup, called its **genotype**, and its physical traits, called its **phenotype**. For example, the GG parent and the Gg offspring have the same phenotype (green pods) but different genotypes.

Lesson Summary

- Genetics is the branch of biology that focuses on heredity in organisms.
- Modern genetics is based on Mendel's explanation of how traits are passed from generation to generation.
- Mendel's use of mathematics in his pea plant studies was important to the confidence he had in his results.
- Mendel carried out his first experiments with true-breeding plants and continued them over a span of three generations.
- For each of the seven characteristics Mendel studied, he observed a similar ratio in the inheritance of dominant to recessive traits (3:1) in the F_2 generation.
- Mendel developed a theory that explained simple patterns of inheritance in which two alleles are inherited to result in one of several traits in offspring.
- The law of segregation states that a pair of alleles is segregated during the formation of gametes and that each gamete has an equal chance of getting either one of the allele.
- The law of independent assortment states that the inheritance of one trait will not affect the inheritance of another. That is, genes are inherited independently of each other.
- Linked genes are genes that are close together on the same chromosome. Linked genes are inherited together.
- Mendelian inheritance patterns can be seen in humans. Albinism is a genetic disorder that is inherited as a simple Mendelian trait.
- Genotype determines phenotype. A homozygous dominant or a heterozygous genotype will always show a dominant phenotype. A homozygous recessive genotype can only show a recessive phenotype.

Review Questions

1. Why was Mendel's understanding of mathematics and science important for his research?
2. What did Gregor Mendel contribute to the science of genetics?
3. What is a true-breeding plant?
4. How was Mendel able to control the pollination of his pea plants?
5. How does cross-pollination differ from self-pollination?
6. How did the appearance of Mendel's F_1 generation differ from the appearance of the P generation?
7. Identify the relationship between genes and alleles.
8. Summarize the law of segregation.
9. Summarize the law of independent assortment.
10. Relate the term homozygous to heterozygous by using an example from Mendel's experiments.
11. Relate the term genotype to phenotype by using an example from Mendel's experiments.
12. Why can't you always identify the genotype of an organism from its phenotype?

Points to Consider

Next we will examine Mendelian Inheritance in further detail.

- Do you think all inheritance is as straightforward as the inheritance in pea plants?
- Is there a relationship between inheritance and probability? What might that relationship be?

7.2 Mendelian Inheritance

Lesson Objectives

- Identify how probability is used to predict outcomes of genetic crosses.
- Outline how a Punnett Square helps predict outcomes of genetic crosses.
- Identify how probability can help determine the alleles in a gamete.
- Identify how a testcross is used to determine the genotype of an organism.
- Describe how monohybrid and dihybrid crosses differ.
- Identify the ratio of phenotypes that appeared in Mendel's dihybrid crosses.
- Examine how a pedigree is used in the study of human inheritance.
- Describe how codominance does not follow Mendelian Inheritance.
- Describe how incomplete dominance does not follow Mendelian Inheritance.
- Identify examples of polygenic traits in humans.
- Outline how heredity and environment can interact to affect phenotype.

Introduction

A **Mendelian trait** is a trait that is controlled by a single gene that has two alleles. One of these alleles is dominant and the other is recessive. Several inheritable conditions in humans are passed to offspring in a simple Mendelian fashion. Medical professionals use Mendel's laws to predict and understand the inheritance of certain traits in their patients. Also, farmers, animal breeders, and horticulturists who breed organisms can predict outcomes of crosses by understanding Mendelian inheritance.

Calculating Probability

The rules of probability that apply to tossing a coin or throwing a dice also apply to the laws of segregation and independent assortment. **Probability** is the likelihood that a certain event will occur . It is expressed by comparing the number of events that occur to the total number of possible events. The equation is written as:

Probability = (number of times an event is expected to occur/total number of times an event could happen)

For example, in Mendel's F_2 hybrid generation, the dominant trait of purple flower color appeared 705 times, and the recessive trait appeared 224 times. The dominant allele appeared 705 times out of a possible 929 times (705+224=929).

Probability = (705/929)

(705/929)= 0.76

Probability is normally expressed in a range between 0 and 1, but it can also be expressed as a percentage, fraction, or ratio. Expressed as a percentage, the probability that a plant of the F_2 generation will have purple flowers is 76%. Expressed as a fraction it is about 3/4;,and as a ratio it is roughly 3:1. The probability of the expression of the dominant allele for other characteristics can also be calculated the same way. In fact, Mendel found that all the other dominant "factors" had approximately a 3/4 probability of being expressed in the F_2 hybrid generation. The probability the recessive trait will appear in the F_2 hybrid generation is calculated in the same way.

Probability = (224/929)

(224/929) = 0.24

The probability of the recessive trait appearing in the F_2 generation is 24% or about 1/4.

Results predicted by probability are most accurate when many trials are done. The best way to illustrate this idea is to toss a coin. Because a coin has two sides, every time you toss it the chance of tossing heads or tossing tails is 50%. The outcome of each separate toss is unaffected by any previous or future result. For example, imagine you tossed seven heads in a row. You would think that the next toss is more likely to be a tail, but the possibility of tossing another head is still 50%. If you tossed the coin a total of ten times, a total of seven heads and three tails, you would calculate the probability of tossing heads is 70%. The fact that you carried out only a small number of trials has affected your results. If Mendel had grown only 10 plants, he would have gotten different probabilities for the appearance of dominant and recessive traits. However, Mendel carried out many thousands of trials. He was therefore sure that his results were due to probability, and not to chance.

Probability and the Law of Segregation

Each coin toss is a separate event. Likewise, gamete formation is a separate event. The probability that a Pp heterozygote produces gametes with a P allele or a p allele is 50% for each gamete cell. In a fertilization involving two such plants (as in the F_1 generation self-pollination experiment), each pollen cell and each egg cell have a 50% chance of having the P or p allele.

Predicting Genotypes with Punnett Squares

Mendel developed the law of segregation by following only a single characteristic, such as pod color, in his pea plants. Biologists use a diagram called a **Punnett Square**, to help predict the probable inheritance of alleles in different crosses. In a monohybrid cross, such as the one in **Figure** below, the Punnett square shows every possible combination when combining one maternal (mother) allele with one paternal (father) allele. In this example, both organisms are heterozygous for flower color Pp (purple). Both plants produce gametes that contain both the P and p alleles. The probability of any single offspring showing the dominant trait is 3:1, or 75%.

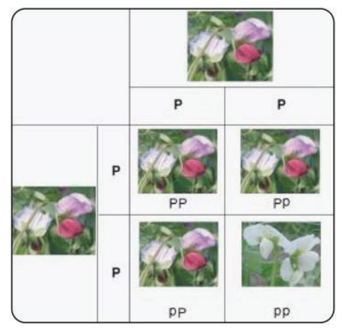


FIGURE 7.7

A Punnett square helps determine the genotype of this heterozygous cross. Two pea plants, both heterozygous for flower color, are crossed. The offspring will show the dominant purple coloration in a 3:1 ratio. Or, about 75% of the offspring will be purple.

Using Probability in a Heterozygous Cross

We can calculate the probability of any one of the offspring being heterozygous (Pp) or homozygous (PP or pp) for flower color. The probability of a plant inheriting the P or p allele from a heterozygous parent is 1/2. Multiply the probabilities of inheriting both alleles to find the probability that any one plant will be a pp homozygote.

$1/2 \times 1/2 = 1/4$ or 0.25

Only 25 %, or one outcome out of four, will result in a plant homozygous for white flower color (pp). The possibility that any one plant will be a PP homozygote is also 1/4. The heterozygous allele combination can happen twice (Pp or pP), so the two probabilities are added together 1/4 + 1/4 = 2/4, or 1/2. The probability that an offspring plant will be Pp heterozygous is 1/2.

Testcross and Punnett Squares

Suppose you have a purple and white flower and, as discussed above, purple color is dominant to white. The white flower must be homozygous for the recessive allele, but the genotype of the purple flower is unknown. It could be either PP or Pp. A testcross will determine the organism's genotype. In a **testcross**, the individual with the unknown genotype is crossed with a homozygous recessive individual (**Figure** below). The unknown genotype can be determined by observing the phenotypes of the resulting offspring.

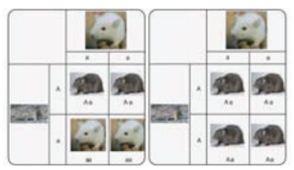


FIGURE 7.8

A testcross helps reveal the genotype of an organism when that organism shows the dominant trait, such as agouti coat color in rats. Such an organism could be homozygous dominant or heterozygous. Agouti is the common color of the Norway rat,

Mendelian Inheritance in Humans

A **pedigree** is a chart which shows the inheritance of a trait over several generations. A pedigree is commonly created for families, and it outlines the inheritance patterns of genetic disorders. **Figure** below shows a pedigree depicting recessive inheritance of a disorder through three generations. Scientists can tell the genetics of inheritance from studying a pedigree, such as whether the trait is sex-linked (on the X or Y chromosome) or autosomal (on a chromosome that does not determine sex), whether the trait is inherited in a dominant or recessive fashion, and possibly whether individuals with the trait are heterozygous or homozygous.

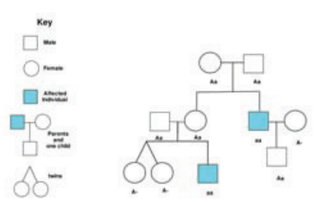


FIGURE 7.9

In a pedigree, squares symbolize males, and circles represent females. A horizontal line joining a male and female indicates that the couple had offspring. Vertical lines indicate offspring which are listed left to right, in order of birth. Shading of the circle or square indicates an individual who has the trait being traced. The inheritance of the recessive trait is being traced. A is the dominant allele and a is recessive.

Is the trait sex-linked or autosomal? A **sex chromosome** is a chromosome that determines the sex of an organism. Humans have two sex chromosomes, X and Y. Females have two X chromosomes (XX), and males have one X and one Y (XY). An **autosome** is any chromosome other than a sex chromosome. If a trait is autosomal it will affect males and females equally.

A **sex-linked trait** is a trait whose allele is found on a sex chromosome. The human X chromosome is significantly larger than the Y chromosome; there are many more genes located on the X chromosome than there are on the Y chromosome. As a result there are many more X-linked traits than there are Y-linked traits. Most sex-linked traits are recessive. Because males carry only one X chromosome, if they inherit a recessive sex-linked gene they will show a sex-linked condition.

Because of the recessive nature of most sex-linked traits, a female who shows a sex-linked condition would have to have two copies of the sex-linked allele, one on each of her X chromosomes. **Figure** below shows how red-green colorblindness, a sex-linked disorder, is passed from parent to offspring.

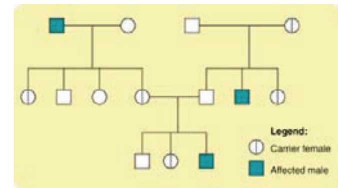


FIGURE 7.10

An X-linked disorder such as red-green colorblindness is normally passed onto the son of a carrier mother. Usually, females are unaffected as they have a second, normal copy of the allele on the second X chromosome. However, if a female inherits two defective copies of the allele, she will be colorblind. Therefore, every son of a colorblind woman will be colorblind.

Is the Trait Dominant or Recessive? If the trait is autosomal dominant, every person with the trait will have a parent with the trait. If the trait is recessive, a person with the trait may have one, both or neither parent with the trait. An example of an autosomal dominant disorder in humans is Huntington's disease (HD). Huntington's disease is a degenerative disease of the nervous system. It has no obvious effect on phenotype until the person is aged 35 to 45 years old. The disease is non-curable and, eventually, fatal. Every child born to a person who develops HD has a 50% chance of inheriting the defective allele from the parent.

Are the Individuals with the Trait Heterozygous or Homozygous? If a person is homozygous or heterozygous for the dominant allele of a trait, they will have that trait. If the person is heterozygous for a recessive allele of the trait, they will not show the trait. A person who is heterozygous for a recessive allele of a trait is called a **carrier**. Only people who are homozygous for a recessive allele of a trait will have the trait.

Non-Mendelian Modes of Inheritance

The relationship between genotype and phenotype is rarely as simple as the examples Mendel studied. Each characteristic he studied had two alleles, one of which was completely dominant and the other completely recessive. Geneticists now know that alleles can be codominant, or incompletely dominant.

Codominance

Codominance occurs when both traits appear in a heterozygous offspring. Neither allele is completely dominant nor completely recessive. For example, roan shorthorn cattle have codominant genes for hair color. The coat has both red and white hairs. The letter R indicates red hair color, and R' white hair color. In cases of codominance, the genotype of the organism can be determined from its phenotype. The heifer in **Figure** below is RR' heterozygous for coat color.

FIGURE 7.11

The roan coat of this shorthorn heifer is made up of red and white hairs. Both the red and white hair alleles are codominant. Therefore cattle with a roan coat are heterozygous for coat color (RR

Incomplete Dominance

Incomplete dominance occurs when the phenotype of the offspring is somewhere in between the phenotypes of both parents; a completely dominant allele does not occur. For example, when red snapdragons (C^RC^R)</math> are crossed with white snapdragons (C^WC^W), the F_1 hybrids are all pink hetrozygotes for flower color (C^RC^W). The pink color is an intermediate between the two parent colors. When two F_1 (C^RC^W) hybrids are crossed they will produce red, pink, and white flowers. The genotype of an organism with incomplete dominance can be determined

from its phenotype (**Figure** below).

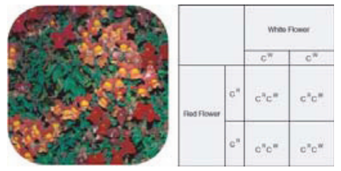


FIGURE 7.12

Snapdragons show incomplete dominance in the traits for flower color. The offspring of homozygous red-flowered and homozygous white-flowered parents are heterozygous pink-flowered.

Complex Forms of Heredity

Traits that are affected by more than one gene are called **polygenic traits**. The genes that affect a polygenic trait may be closely linked on a chromosome, unlinked on a chromosome, or on different chromosomes. Polygenic traits are often difficult for geneticists to track because the polygenic trait may have many alleles. Also, independent assortment ensures the genes combine differently in gametes. Therefore, many different intermediate phenotypes exist in offspring. Eye color (**Figure** below), and skin color are examples of polygenic traits in humans.

FIGURE 7.13

Eye color and skin color are examples of polygenic traits; they are influenced by more than one gene.

When three or more alleles determine a trait, the trait is said to have **multiple alleles**. The human ABO blood group is controlled by a single gene with three alleles: i, I^A, I^B, and the recessive i allele. The gene encodes an enzyme that affects carbohydrates that are found on the surface of the red blood cell. A and B refer to two carbohydrates found on the surface of red blood cells. There is not an O carbohydrate. Type O red blood cells do not have either type A or B carbohydrates on their surface.

The alleles I^A and I^B are dominant over i. A person who is homozygous recessive ii has type O blood. Homozygous dominant I^AI^A or heterozygous dominant I^Ai have type A blood, and homozygous dominant I^BI^B or heterozygous dominant I^Bi have type B blood. I^AI^B people have type AB blood, because the A and B alleles are codominant. Type A and type B parents can have a type AB child. Type A and a type B parent can also have a child with Type O blood, if they are both heterozygous (I^Bi,I^Ai). The table (7.3"Bloodtype as Determined by Multiple Alleles") shows how the different combinations of the blood group alleles can produce the four blood groups, A, AB, B, and O.

TABLE 7.3: **Bloodtype as Determined by Multiple Alleles**

	I^A	I^B	i
I^A	I^AI^A TYPE A	I^AI^B TYPE AB	I^Ai TYPE A
I^B	I^A I^B TYPE AB	I^B I^B TYPE B	I^B i TYPE B
i	i I^A TYPE A	i I^B TYPE B	ii TYPE O

Lesson Summary

- Probability is the likelihood that a certain event will occur. It is expressed by comparing the number of events that actually occur to the total number of possible events. Probability can be expressed as a fraction, decimal, or ratio.
- A Punnett square shows all the possible genotypes that can result from a given cross.
- A testcross examines the genotype of an organism that shows the dominant phenotype for a given trait. The heterozygous organism is crossed with an organism that is homozygous recessive for the same trait.
- A dihybrid cross-examines the inheritance of two traits at the same time.
- A pedigree can help geneticists discover if a trait is sex-linked, if it is dominant or recessive, and if the person (or people) who have the trait are homozygous or heterozygous for that trait.
- The Mendelian pattern of inheritance and expression does not apply to all traits. Codominant traits, incompletely dominant traits, and polygenic traits do not follow simple Mendelian patterns of inheritance. Their inheritance patterns are more complex.

Review Questions

1. What does the probability equation help to determine?
2. How can probability be expressed?
3. Outline how Punnett squares are useful.
4. Identify the purpose of a testcross.
5. How do the Punnett squares for a monohybrid cross and a dihybrid cross differ?
6. Mendel carried out a dihybrid cross to examine the inheritance of the characteristics for seed color and seed shape. The dominant allele for yellow seed color is Y, and the recessive allele for green color is y. The dominant allele for round seeds is R, and the recessive allele for a wrinkled shape is r. The two plants that were crossed were F1 dihybrids RrYy. Identify the ratios of traits that Mendel observed in the F2 generation, and explain in terms of genotype what each number means. Create a Punnett square to help you answer the question.
7. Draw a pedigree that illustrates the passing of the dominant cleft chin trait through three generations. A person who has two recessive alleles does not have a cleft chin. Let us say that C is the dominant allele, c is the recessive allele.
8. A classmate tells you that a person can have type AO blood. Do you agree? Explain.
9. Mendelian inheritance does not apply to the inheritance of alleles that result in incomplete dominance and codominance. Explain why this is so.

Vocabulary Students need to Learn:

Autosome, Dominant trait, Recessive Trait, Heredity, Genetics, Pedigree, Probability, Sex Chromosomes, Phenotype, Genotype, Hybrid, Fertilization, Law of Independent, Homozygous, Heterozygous, Assortment, Law of Segregation, Genetics, Artificial Selection, Genetic Engineering, Allele, Chromosome

The next chapter is *Molecular Genetics.*

- What do you think Molecular Genetics refers to?
- How can DNA contain all the genetic information?
- If DNA is in the nucleus, and proteins are made on ribosomes in the cytoplasm, how do you think this happens?

7.3 References

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CHAPTER 8 The Story of DNA - Edited

Chapter Outline

8.1 DNA and RNA

Lesson Objectives

- Explain how the structure and replication of DNA are essential to heredity and protein synthesis.
- Discuss how the work of Griffith, Avery, Hershey, and Chase demonstrated that DNA is the genetic material.
- Define transformation and explain that transformation is the change in genotype and phenotype due to the assimilation of the external DNA by a cell.
- Discuss the findings of Chargaff. Describe the importance of the finding that in DNA, the amount of adenine and thymine were about the same and that the amount of guanine and cytosine were about the same. This finding lead to the base pairing rules.
- Explain Watson and Crick's double helix model of DNA.
- Describe the structure of DNA.
- Describe how DNA is replicated.
- Explain the importance of the fact that during DNA replication, each strand serves as a template to make a complementary DNA strand.
- Describe the structure and function of RNA.
- Discuss the role of the three types of RNA: mRNA, rRNA, and tRNA.

Introduction

What tells the first cell of an organism what to do? How does that first cell know to become two cells, then four cells, and so on? Does this cell have instructions? What are those instructions and what do they really do? What happens when those instructions don't work properly? Are the "instructions" the genetic material? Though today it seems completely obvious that Deoxyribonucleic acid, or **DNA**, is the genetic material, this was not always known.

DNA and RNA

Practically everything a cell does, be it a liver cell, a skin cell, or a bone cell, it does because of proteins. It is your proteins that make a bone cell act like a bone cell, a liver cell act like a liver cell, or a skin cell act like a skin cell. In other words, it is the proteins that give an organism its traits . We know that it is your proteins that that make you tall or short, have light or dark skin, or have brown or blue eyes. But what tells those proteins how to act? It is the structure of the protein that determines what it does. And it is the order and type of **amino acids** that determine the structure of the protein. And that order and type of amino acids that make up the protein are determined by your DNA sequence.

The relatively large chromosomes that never leave the nucleus are made of DNA. And, as proteins are made on the ribosomes in the cytoplasm, how does the information encoded in the DNA get to the site of protein synthesis? That's where RNA comes into this three-player act.

DNA → RNA → Amino acids → Protein

This is known as the **central dogma** of molecular biology. It states that "DNA makes RNA makes protein." This process starts with DNA. First, DNA had to be identified as the genetic material.

The Hereditary Material

For almost 100 years, scientists have known plenty about proteins. They have known that proteins of all different shapes, sizes, and functions exist. For this reason, many scientists believed that proteins were the heredity material. It wasn't until 1928, when Frederick Griffith identified the process of transformation, that individuals started to question this concept. Griffith demonstrated that transformation occurs, but what was the material that caused the transforming process?

Griffith, Avery, Hershey and Chase

Griffith was studying *Streptococcus pneumoniae*, a bacterium that infects mammals. He used two strains, a virulent S (smooth) strain and a harmless R (rough) strain to demonstrate the transfer of genetic material. The S strain is surrounded by a polysaccharide capsule, which protects it from the host's immune system, resulting in the death of the host, while the R strain, which does not have the protective capsule, is defeated by the host's immune system. Hence, when mammalian cells are infected with the R strain bacteria, the host does not die (**Figure** 8.1).

Griffith infected mice with heat-killed S strain bacteria. As expected, the heat-killed bacteria, as they were dead, had no effect on the mice (Figure 1). But then he tried something different. He mixed the remains of heat-killed S strain bacteria with live R strain bacteria and injected the mixture into mice. Remember, separately both of these bacteria are harmless to the mice. And yet the mice died. Why? These mice had both live R and live S strain bacteria in their blood. How? Griffith concluded that the R strain had changed, or transformed, into the lethal S strain. Something, such as the "instructions" from the remains of the S strain, had to move into the R strain in order to turn the harmless R strain into the lethal S strain. This material that was transferred between strains had to be the heredity material. But the transforming material had yet to be identified. **Transformation** is now known as the change in genotype and phenotype due to the assimilation of external DNA (heredity material) by a cell.

Over the next decade, scientists, led by Oswald Avery, tried to identify the material involved in transformation. Avery, together with his colleagues Maclyn McCarty and Colin MacLeod, removed various organic compounds from bacteria and tested the remaining compounds for the ability to cause transformation. If the remaining material did not cause transformation, then that material could not be the heredity material. Avery treated S strain bacteria with protease enzymes, which remove proteins from cells, and then mixed the remainder with R strain bacteria. The R strain bacteria transformed, meaning that proteins did not carry the genes for causing the disease. Then the remnants of the S strain bacteria were treated with **deoxyribonuclease**, an enzyme which degrades DNA. After this treatment, the R strain bacteria no longer transformed. This indicated that DNA was the heredity material. The year was 1944.

However, this finding was not widely accepted, partly because so little was known about DNA. It was still thought that proteins were better candidates to be the heredity material. The structure of DNA was still unknown, and many scientists were not convinced that genes from bacteria and more complex organisms could be similar.

In 1952, Alfred Hershey and Martha Chase put this skepticism to rest. They conclusively demonstrated that DNA is the genetic material. Hershey and Chase used the T2 **bacteriophage**, a virus that infects bacteria, to prove this point. A virus is essentially DNA (or RNA) surrounded by a protein coat (**Figure** 8.2). To reproduce, a virus must infect a cell and use that host cell's machinery to make more viruses. The T2 bacteriophage can quickly turn an *Escherichia coli (E. coli)* bacteria into a T2 producing system. But to do that, the genetic material from T2, which could only be protein or DNA, must be transferred to the bacteria. Which one was it?

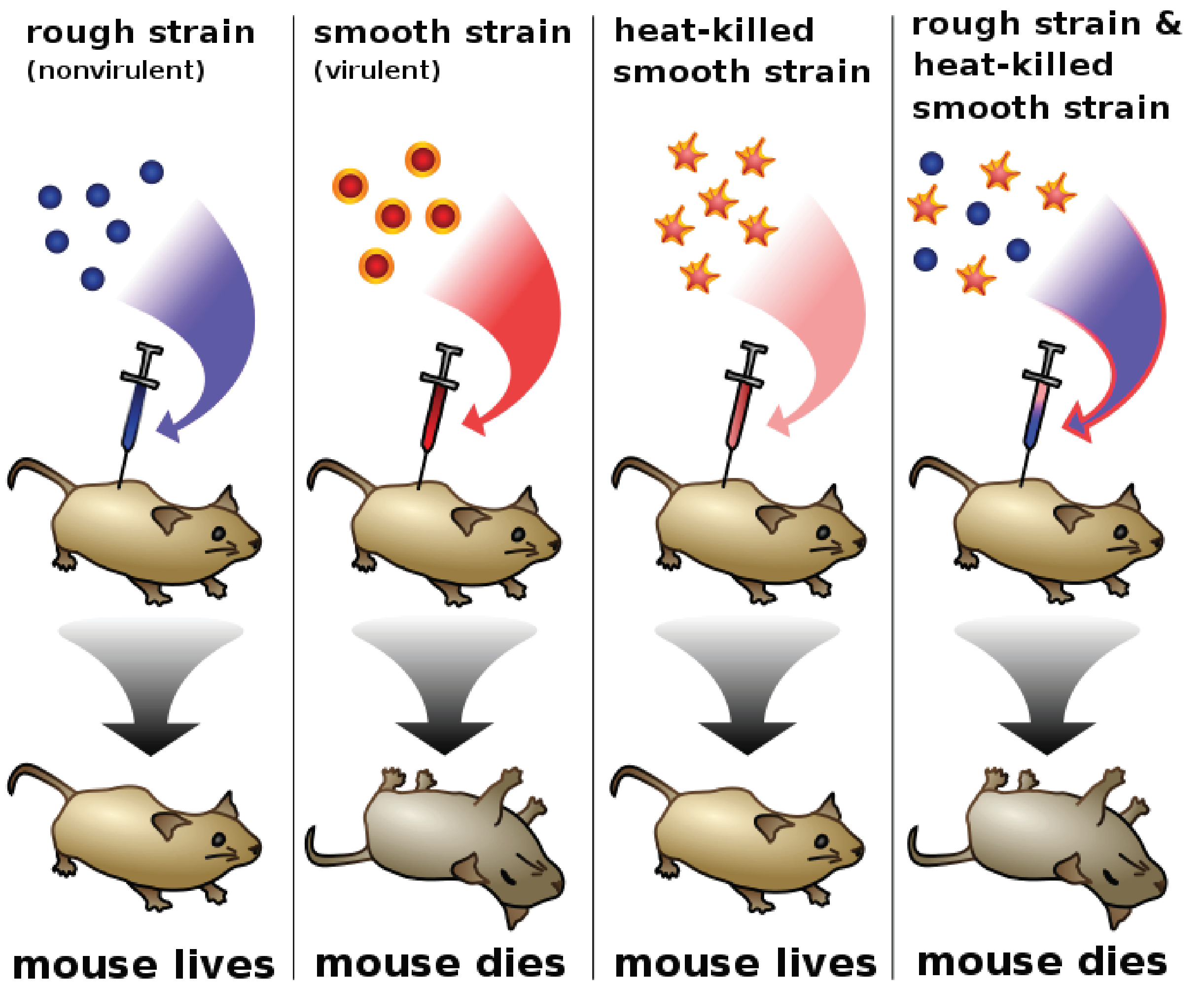

FIGURE 8.1
The transformation experiments of Griffith. The rough (R) strain has no effect on the mouse, whereas the smooth (S) strain is harmful to the mouse. Heat-killed S strain also has no effect on the mouse, but the mixture of heat-killed S strain and the R strain is harmful to the mouse.

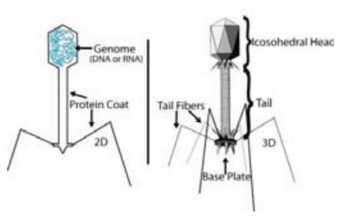

FIGURE 8.2
Structural overview of T2 phage. A 2-dimensional representation is on the left, and a 3-dimensional representation is on the right. The phage is essentially nucleic acid surrounded by a protein coat.

Hershey and Chase performed a series of classic experiments, taking advantage of the fact that T2 is essentially just DNA and protein. In the experiments, T2 phages with either radioactive ^{32}P-labeled DNA or radioactive ^{35}S-labeled protein were used to infect bacteria. Either the radioactive proteins or radioactive DNA would be transferred to the

bacteria. Identifying which one is transferred would identify the genetic material. In both experiments, bacteria were separated from the phage coats by blending, followed by centrifugation. Only the radioactively labeled DNA was found inside the bacteria, whereas the radioactive proteins stayed in the solution (**Figure** 8.3). These experiments demonstrated that DNA is the genetic material and that protein does not transmit genetic information.

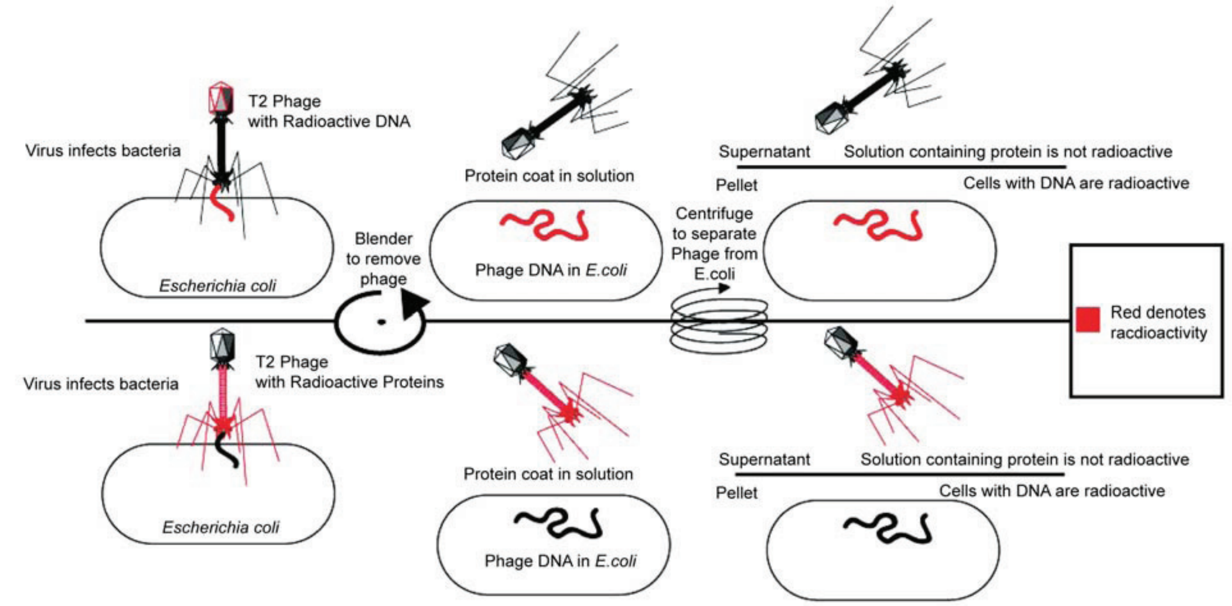

FIGURE 8.3
The Hershey and Chase experiment. T2 virus with either radioactive DNA (upper section) or radioactive protein (lower section) were used to infect bacteria. A blender was used to remove the phage from the bacteria followed by centrifugation. The radioactive DNA was found inside the bacteria (upper section), demonstrating that DNA is the genetic material.

Chargaff's Rules

It was known that DNA is composed of **nucleotides**, each of which contains a nitrogen-containing base, a five-carbon sugar (deoxyribose), and a phosphate group. In these nucleotides, there is one of the four possible bases: adenine (A), guanine (G), cytosine (C), or thymine (T) (**Figure** 8.4).

Erwin Chargaff proposed two main rules that have been appropriately named Chargaff's rules. In 1947 he showed that the composition of DNA varied from one species to another. This molecular diversity added evidence that DNA could be the genetic material. Chargaff also determined that in DNA, the amount of one base always approximately equals the amount of a particular second base. For example, the number of guanines equals the number of cytosines, and the number of adenines equals the number of thymines. Human DNA is 30.9% A and 29.4% T, 19.9% G and 19.8% C. This finding, together with that of the DNA structure, led to the base-pairing rules of DNA.

The Double Helix

In the early 1950s, Rosalind Franklin started working on understanding the structure of DNA fibers. Franklin, together with Maurice Wilkins, used her expertise in x-ray diffraction photographic techniques to analyze the

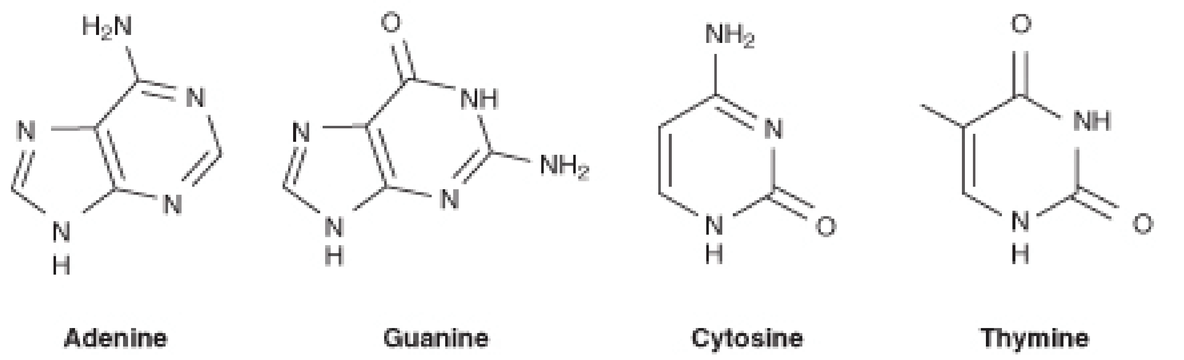

FIGURE 8.4
Chemical structure of the four nitrogenous bases in DNA.

structure of DNA. In February 1953, Francis Crick and James D. Watson of the Cavendish Laboratory in Cambridge University had started to build a model of DNA. Watson and Crick indirectly obtained Franklin's DNA X-ray diffraction data demonstrating crucial information into the DNA structure. Francis Crick and James Watson (**Figure** 8.5) then published their double helical model of DNA in *Nature* on April 25th, 1953.

FIGURE 8.5
Rosalind Franklin

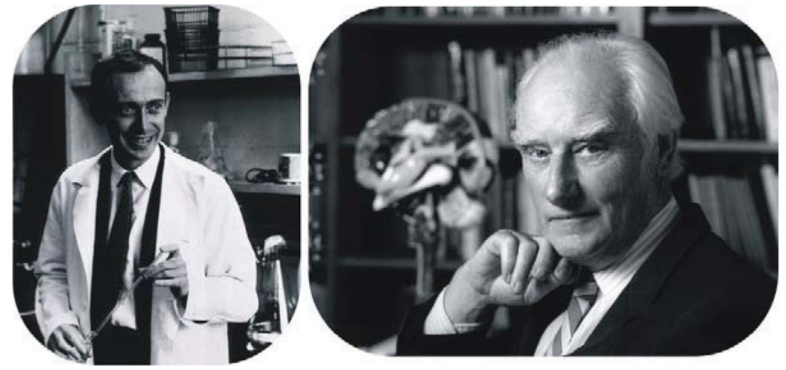

FIGURE 8.6

DNA has the shape of a **double helix**, just like a spiral staircase (**Figure** 8.6). There are two sides, called the **sugar-phosphate backbone**, because they are made from alternating phosphate groups and deoxyribose sugars. The "steps" of the double helix are made from the base pairs formed between the nitrogenous bases. The DNA double helix is held together by hydrogen bonds between the bases attached to the two strands.

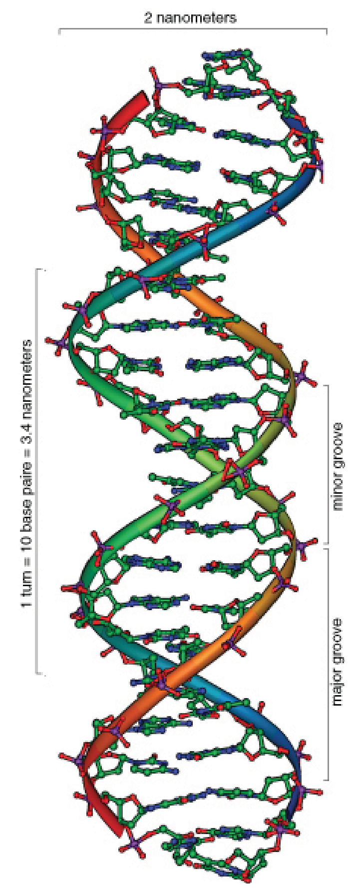

FIGURE 8.7
The DNA double helix. The two sides are the sugar-phosphate backbones, composed of alternating phosphate groups and deoxyribose sugars. The nitrogenous bases face the center of the double helix.

The double helical nature of DNA, together with the findings of Chargaff, demonstrated the base-pairing nature of the bases. Adenine always pairs with thymine, and guanine always pairs with cytosine (**Figure** 8.7). Because of this complementary nature of DNA, the bases on one strand determine the bases on the other strand. These complementary base pairs explain why the amounts of guanine and cytosine are present in equal amounts, as are the amounts of adenine and thymine. Adenine and guanine are known as **purines**. These bases consist of two ring structures. Purines make up one of the two groups of nitrogenous bases. Thymine and cytosine are **pyrimidines**, which have just one ring structure. By having a purine always combine with a pyrimidine in the DNA double helix,

the distance between the two sugar-phosphate backbones is constant, maintaining the uniform shape of the DNA molecule.

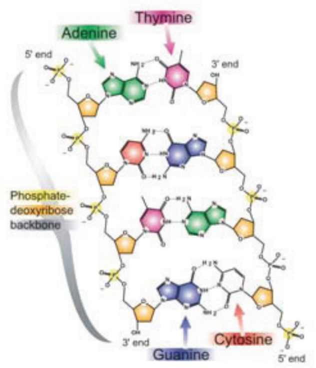

FIGURE 8.8
The base-pairing nature of DNA. Adenine always pairs with thymine, and they are held together with two hydrogen bonds. The guanine-cytosine base pair is held together with three hydrogen bonds.

So it is this four letter code, made of just A, C, G, and T, that determines what the organism will become and what it will look like. How can these four bases carry so much information? This information results from the order of these four bases in the chromosomes. This sequence carries the unique genetic information for each species and each individual. Humans have about 3,000,000,000 bits of this information in each cell. A gorilla may also have close to that amount of information, but a slightly different sequence. For example, the sequence AGGTTTACCA will have different information than CAAGGGATTA. The closer the evolutionary relationship is between two species, the more similar their DNA sequences will be. For example, the DNA sequences between two species of reptiles will be more similar than between a reptile and an elm tree.

DNA sequences can be used for scientific, medical, and forensic purposes. DNA sequences can be used to establish evolutionary relationships between species, to determine a person's susceptibility to inherit or develop a certain disease, or to identify crime suspects or victims. Of course, DNA analysis can be used for other purposes as well. So why is DNA so useful for these purposes? It is useful because every cell in an organism has the same DNA sequence. For this to occur, each cell must have a mechanism to copy its entire DNA. How can so much information be exactly copied in such a small amount of time?

DNA Replication

DNA replication is the process in which a cell's entire DNA is copied, or replicated. This process occurs during the Synthesis (S) phase of the eukaryotic cell cycle. As each DNA strand has the same genetic information, both strands of the double helix can serve as templates for the reproduction of a new strand. The two resulting double helices are identical to the initial double helix. For an animation of DNA replication, see http://www.hhmi.org/biointeractive/media/DNAi_replication_vo1-sm.mov.

RNA

DNA $\rightarrow$ **RNA** $\rightarrow$ **Amino acids** $\rightarrow$ Protein

"DNA makes RNA makes protein." So what exactly is RNA? Ribonucleic acid, or **RNA**, is the other important nucleic acid in the three player act. When we say that "DNA makes RNA makes protein," what do we mean? We mean that the information in DNA is somehow transferred into RNA, and that the information in RNA is then used to make the protein.

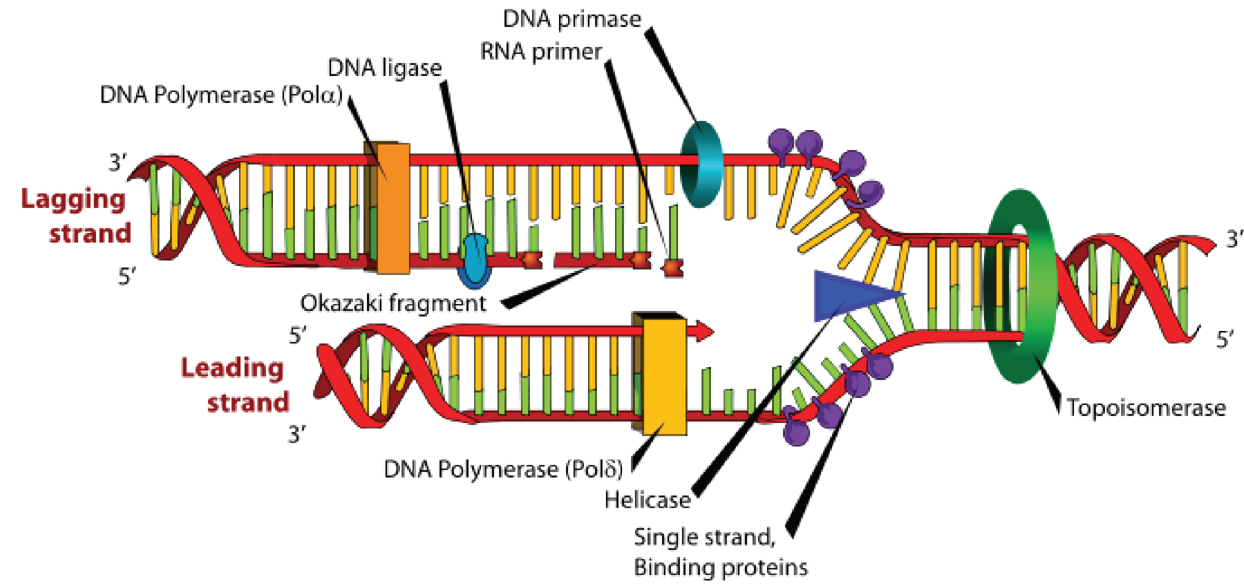

FIGURE 8.9
DNA replication. The two DNA strands are opened by helicase. The strands are held open by a single strand of binding proteins, preventing premature reannealing. Topoisomerase solves the problem caused by tension generated by winding/unwinding of DNA. This enzyme wraps around DNA and makes a cut permitting the helix to spin and relax. Once DNA is relaxed, topoisomerase reconnects broken strands. DNA primase synthesizes a short RNA primer which initiates the Okazaki fragment. Okazaki fragments are attached by DNA ligase.

To understand this, it helps to first understand RNA. A **gene** is a segment of DNA that contains the information necessary to encode an RNA molecule or a protein. Keep in mind that even though you have many thousands of genes, not all are used in every cell type. In fact, probably only a few thousand are used in a particular type of cell, with different cell types using different genes. However, while these genes are embedded in the large chromosomes that never leave the nucleus, the RNA is relatively small and is able to carry information out of the nucleus.

RNA Structure

RNA structure differs from DNA in three specific ways. Both are nucleic acids and made out of nucleotides; however, RNA is single stranded while DNA is double stranded. RNA contains the 5-carbon sugar ribose, whereas in DNA, the sugar is deoxyribose. Though both RNA and DNA contain the nitrogenous bases adenine, guanine and cytosine, RNA contains the nitrogenous base uracil instead of thymine. Uracil pairs with adenine in RNA, just as thymine pairs with adenine in DNA. A comparison of RNA and DNA is shown in **Table** 8.1 8.1A Comparison of RNA and DNA .

TABLE 8.1: A Comparison of RNA and DNA

	RNA	DNA
	single stranded	double stranded
Specific Base	contains uracil	contains thymine
Sugar	ribose	deoxyribose
Size	relatively small	big (chromosomes)

TABLE 8.1: (continued)

	RNA	DNA
Location	moves to cytoplasm	stays in nucleus
Types	3 types: mRNA, tRNA, rRNA	generally 1 type

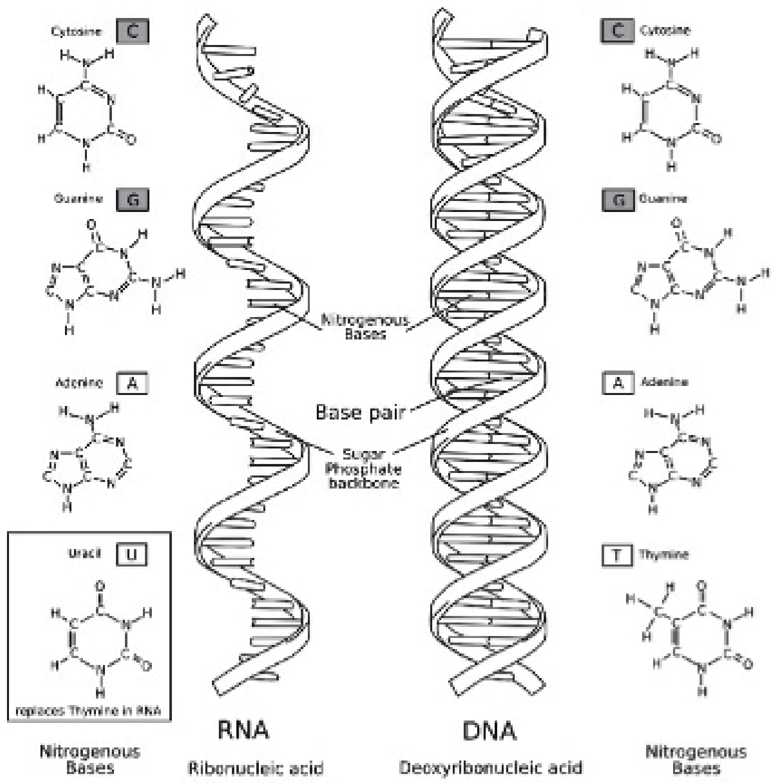

FIGURE 8.10
A comparison of RNA and DNA. RNA is single stranded and contains the base uracil, which replaces thymine.

Three Types of RNAs

So what does RNA do? There are three types of RNA: messenger RNA (mRNA), transfer RNA (tRNA), and ribisomal RNA (rRNA). All three of these nucleic acids work together to produce a protein. The **mRNA** takes the instructions from the nucleus to the cytoplasm, where the ribosomes are located. **Ribosomes** are where the proteins are made. The ribosomes themselves are made out of **rRNA** and other proteins. The mRNA binds to the ribosome, bringing the instructions to order the amino acids to the site of protein synthesis. Finally, the **tRNA** brings the correct amino acid to the site of protein synthesis. In mRNA, the four nucleotides (A, C, G, and U) are arranged into **codons** of three bases each. Each codon encodes for a specific amino acid, except for the stop codons, which terminate protein synthesis. tRNA contains a three base region called the **anticodon**, which can base pair to the corresponding three-base codon region on mRNA.

Remember, proteins are made out of amino acids, so how does the information get converted from the language of nucleotides to the language of amino acids? The process is called **translation**.

Lesson Summary

- Griffith demonstrated the process of transformation, which is the change in genotype and phenotype due to the assimilation of the external DNA by a cell.

- Avery and colleagues demonstrated that DNA was the transforming material.
- The Hershey and Chase experiments conclusively demonstrated that DNA is the genetic material.
- Watson and Crick demonstrated the double helix model of DNA based on Franklin's work with photographs of x-ray diffraction.
- The Base paring rules state that A always pairs with T and G always pairs with C.
- DNA replication is the process by which a cell's entire DNA is copied, or replicated.
- RNA is a single-stranded nucleic acid.
- RNA contains the nitrogenous base uracil.
- There are three types of RNA: mRNA, tRNA, and rRNA.
- mRNA is the intermediary between the nucleus, where the DNA lives, and the cytoplasm, where proteins are made.

Review Questions

1. Discuss how DNA was identified as the genetic material.
2. Define transformation.
3. In DNA, why does the amount of adenine approximately equal the amount of thymine?
4. What are the base pairing rules?
5. Explain Watson and Crick's double helix model of DNA.
6. How is DNA replicated?
7. Discuss the importance of mRNA.
8. Explain the main differences between mRNA, rRNA,and tRNA.

Points to Consider

- "DNA $\rightarrow$ RNA" Can you think of a method in which the information in DNA is transferred to an RNA molecule?
- Can you hypothesize on how the As, Cs, Gs and Us of RNA can code for the 20 amino acids of proteins?
- Can you develop a model in which the three types of RNAs interact to make a protein?

8.2 Protein Synthesis

Lesson Objectives

- Discuss the meaning of DNA → RNA → Protein.
- Describe how transcription makes RNA from a DNA template.
- Explain the various types of modification mRNA undergoes before translation.
- Discuss mRNA splicing and define introns and exons.
- Explain how the Genetic Code is a three letter code, and describe its role in translating nucleotides into amino acids.
- Explain that a reading frame is the group of three bases in which the mRNA is read, and describe how interrupting the reading frame may have severe consequences on the protein.
- Discuss what is meant by the universal genetic code.
- Describe translation. Explain that translation is the process of ordering the amino acids into a polypeptide; translation involves changing the language of nucleotides into the language of amino acids.
- Illustrate the process of translation, describing how mRNA, rRNA, and tRNA all work together to complete the process.
- Discuss what happens to the polypeptide after translation.

DNA → RNA → Amino acids → Protein

The central dogma of molecular biology describes the fundamental process that makes us all different. We all have different proteins. That is, though they may be the same types of proteins, such as we have the protein collagen found in bones, many of our proteins are slightly different and thus work slightly differently. If all our proteins acted the same way, we would all be exactly the same. But because we all have different DNA sequences, and DNA contains genes, and **genes** contain the information to encode an RNA molecule or a protein, we are all different.

So how does "DNA makes RNA makes protein" actually happen? The two processes necessary to make a protein from the information in DNA are transcription and translation. Transcription, which happens in the nucleus, uses the DNA sequence to make an RNA molecule. The RNA then leaves the nucleus and goes to the cytoplasm where **translation occurs on a ribosome** and produces a protein .

Transcription

Transcription is "DNA → RNA." In other words, transcription is the transfer of the genetic "instructions" from DNA to RNA. During transcription, a complementary copy of RNA is made. Whereas in DNA replication both strands of the DNA double helix are used as templates, in transcription only one strand is needed. RNA polymerase enzymatically "reads" a template strand of DNA, known as the coding strand, to synthesize the complementary RNA strand. Transcription is divided into 3 stages, appropriately named initiation, elongation and termination.

Initiation

Transcription begins with the binding of RNA polymerase to the promoter of a gene. A eukaryotic promoter usually includes specific sequences that are recognized by transcription factors, which are proteins that aid in the binding of RNA polymerase to the correct place on the DNA. The transcription initiation complex formed by the promoter,

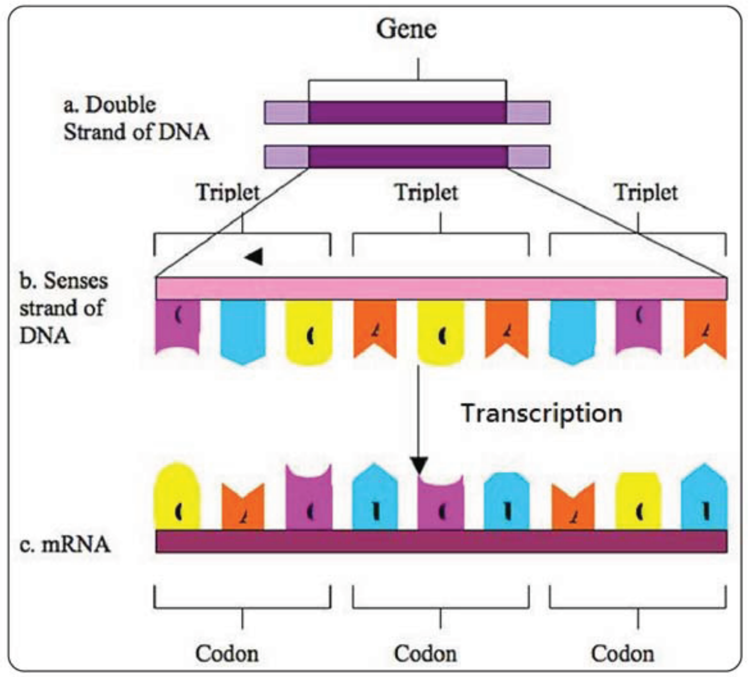

FIGURE 8.11
Figure 8.9 Each gene (a) contains triplets of bases (b) that are transcribed into RNA (c). Every triplet, or codon, encodes for a unique amino acid.

transcription factors, and RNA polymerase signals the start, or **initiation**, of transcription. The DNA unwinds and produces a small open complex, which allows **RNA polymerase** to "read" the DNA template and begin the synthesis of RNA.

The Genetic Code

So how exactly is the language of nucleotides used to code for the language of amino acids? How can a code of only As, Cs, Gs, and Us carry information for 20 different amino acids? The **genetic code** is the code in which the language of nucleotides is used to create the language of amino acids.

Cracking the Code

A code of at least three letters has to be the answer. A one letter code would only be able to code for four amino acids. A two letter code could only code for 16 amino acids. With a three letter code, there are 64 possibilities. As there are 20 amino acids, the answer must be a code of at least three letters.

In 1961, Francis Crick and Sydney Brenner demonstrated the presence of codons, that is, three bases of RNA that code for one amino acid (**Figure** 8.10). Also in 1961, Marshall Nirenberg and Heinrich Matthaei at the National Institutes of Health (NIH) demonstrated that a poly(U) RNA sequence was translated into a polypeptide consisting of only the amino acid phenylalanine. This proved that the codon UUU coded for the amino acid phenylalanine. Extending this work, Nirenberg and his coworkers were able to determine the nucleotide makeup of 54 of the 64 codons. Others determined the remainder of the genetic code (**Figure** 8.11).codons.

Start and Stop Codons

The codon AUG codes for the amino acid methionine. This codon is also the start codon which begins every translation of every amino acid chain. The translational machinery "reads" the mRNA codon by coding until it

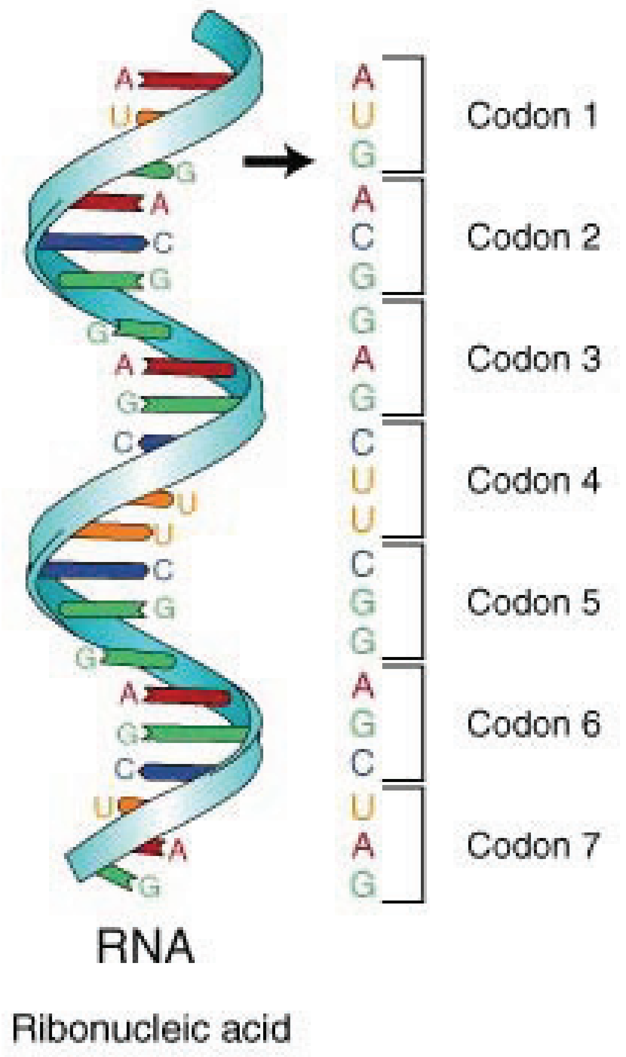

FIGURE 8.12
Figure 8.10

reaches a stop, or termination, codon. Stop codons are only associated with mRNA, not tRNA or r RNA. There are three stop codons: UAG, UGA, UAA.

The Reading Frame

The **reading frame** is the frame of three bases in which the mRNA is read or translated. Every sequence can be read in three reading frames, each of which will produce a different amino acid sequence. For example, in the sequence GCAUGGGGGUCUAG, the **translation** starts with the start codon which consists of the three bases AUG. Each subsequent codon is translated until an in-frame stop codon is reached. In the example above, the polypeptide sequence would be: methionine – glycine – valine – stop.

Mutations that disrupt the reading frame by insertions or deletions of a non-multiple of 3 nucleotide bases are known as **frameshift mutations**. Take the example:

MR BLAKE IS A GOOD TEACHER

A deletion mutation that disrupts the reading frame, results in a message that does not make any sense or adds a

1st base	2nd base: U	2nd base: C	2nd base: A	2nd base: G
U	UUU (Phe/F) Phenylalanine	UCU (Ser/S) Serine	UAU (Tyr/Y) Tyrosine	UGU (Cys/C) Cysteine
U	UUC (Phe/F) Phenylalanine	UCC (Ser/S) Serine	UAC (Tyr/Y) Tyrosine	UGC (Cys/C) Cysteine
U	UUA (Leu/L) Leucine	UCA (Ser/S) Serine	UAA Ochre (*Stop*)	UGA Opal (*Stop*)
U	UUG (Leu/L) Leucine	UCG (Ser/S) Serine	UAG Amber (*Stop*)	UGG (Trp/W) Tryptophan
C	CUU (Leu/L) Leucine	CCU (Pro/P) Proline	CAU (His/H) Histidine	CGU (Arg/R) Arginine
C	CUC (Leu/L) Leucine	CCC (Pro/P) Proline	CAC (His/H) Histidine	CGC (Arg/R) Arginine
C	CUA (Leu/L) Leucine	CCA (Pro/P) Proline	CAA (Gln/Q) Glutamine	CGA (Arg/R) Arginine
C	CUG (Leu/L) Leucine	CCG (Pro/P) Proline	CAG (Gln/Q) Glutamine	CGG (Arg/R) Arginine
A	AUU (Ile/I) Isoleucine	ACU (Thr/T) Threonine	AAU (Asn/N) Asparagine	AGU (Ser/S) Serine
A	AUC (Ile/I) Isoleucine	ACC (Thr/T) Threonine	AAC (Asn/N) Asparagine	AGC (Ser/S) Serine
A	AUA (Ile/I) Isoleucine	ACA (Thr/T) Threonine	AAA (Lys/K) Lysine	AGA (Arg/R) Arginine
A	AUG[A] (Met/M) Methionine	ACG (Thr/T) Threonine	AAG (Lys/K) Lysine	AGG (Arg/R) Arginine
G	GUU (Val/V) Valine	GCU (Ala/A) Alanine	GAU (Asp/D) Aspartic acid	GGU (Gly/G) Glycine
G	GUC (Val/V) Valine	GCC (Ala/A) Alanine	GAC (Asp/D) Aspartic acid	GGC (Gly/G) Glycine
G	GUA (Val/V) Valine	GCA (Ala/A) Alanine	GAA (Glu/E) Glutamic acid	GGA (Gly/G) Glycine
G	GUG (Val/V) Valine	GCG (Ala/A) Alanine	GAG (Glu/E) Glutamic acid	GGG (Gly/G) Glycine

nonpolar polar basic acidic (stop codon)

FIGURE 8.13
Figure 8.11 The Genetic Code. The Genetic Code: Codons are in the mRNA sequence. The three letter and one letter code for the amino acids are shown. To read the code, find the first base on the left, the second base at the top, and the third base in the center of the table. For example, the codon GGG codes for the amino acid glycine (as does GGC, GGA, and GGU), CCG codes for Proline, UUA codes for Leucine, and AAG codes for Lysine. There are 64 codons that code for 20 amino acids and three stop codons, so an amino acid may have more than one corresponding codon.

different meaning. If an ‘O’ is deleted:

MR BLAKE IS A GOD TEACHER

Now Mr. Blake is a teacher of Gods. Who did teach Zeus? Was Mr. Blake Thor’s tutor when he was a child?

An insertion mutation that disrupts the reading frame, results in a message that does not make any sense or adds a different meaning. If an ‘S’ is inserted:

MRS BLAKE IS A GOOD TEACHER

Now the gender of the teacher is changed which gives you a new picture of who your teacher is.

Once the reading frame is disrupted, the mRNA may not be translated properly. These mutations may impair the

function of the resulting protein, if the protein is even formed. Many frameshift mutations result in a premature stop codon, in other words, a stop codon that comes earlier than normal during translation. This would result in a smaller protein, most likely without normal function.

Degeneracy of the Universal Genetic Code

When there are 64 codon combinations for 20 amino acids (and stop codons), there is going to be some overlap. Within the genetic code there is redundancy but no ambiguity. For example, the codons GGG, GGA, GGC, and GGU all encode the amino acid glycine, but none encode another amino acid. Degenerate codons often differ in the third position.

The genetic code is said to be universal. That is, the same code is utilized by the simplest prokaryotic organism and by humans. This universality is a tremendous benefit to mankind. If a human gene is placed in a bacteria, it looks just like a piece of DNA to the bacteria. The human As, Cs, Gs, and Ts look just like the bacteria's As, Cs, Gs, and Ts. So, the bacterial proteins will transcribe and translate this DNA, making a human protein.

But how exactly are these proteins made? We have been referring to mRNA's, tRNA's, ribosomes, codons and the genetic code throughout this chapter. How do they all come together to make a protein? The process is called translation.

Translation

Translation is "RNA $\rightarrow$ protein." In other words, translation is the transfer of the instructions in RNA to a protein made of amino acids. Translation uses the products of transcription, mRNA, tRNA, and rRNA, and converts the mRNA sequence into a polypeptide chain according to the genetic code. The mRNA moves to the cytoplasm and interacts with a **ribosome**, which serves as the site of translation.

Lesson Summary

- "DNA makes RNA makes protein" is the central dogma of molecular biology.
- Transcription is the transfer of the genetic instructions from DNA to RNA.
- Translation is the process of using the information in the mRNA to order amino acids into a polypeptide.
- Transcription begins with the binding of RNA polymerase to the promoter of a gene.
- A codon is a three base code for one amino acid.
- Start and stop codons signal the beginning and end of translation.
- There are three stop codons.
- The reading frame is the frame of three bases in which the mRNA is read.
- The genetic code is universal.
- Translation involves the interactions of the three types of RNA. The translation of these amino acids creates a protein.

Review Questions

1. What is meant by "DNA $\rightarrow$ RNA $\rightarrow$ Amino acids $\rightarrow$ Protein?"
2. Describe transcription.
3. Describe the role of the Genetic Code in translation.
4. What is a reading frame?
5. Discuss what is meant by the universal genetic code.
6. Explain translation.

Supplemental Links

- Transcription Animation

http://www-class.unl.edu/biochem/gp2/m_biology/animation/gene/gene_a2.html

- Genetic Science Learning Center:

http://learn.genetics.utah.edu/units/basics/transcribe/

Points to Consider

We know what happens when everything goes right. The result is a correctly made protein that functions properly and maintains homeostasis.

- However, what happens when things do not go right? What can lead to a protein not being made correctly or not functioning correctly?
- Can you think of possible mechanisms that may that can interfere with protein synthesis?
- How can a change in the DNA sequence lead to a different protein?

8.3 Mutation

Lesson Objectives

- Define mutation.
- Describe common causes of mutation.
- Describe common types of mutation.
- Illustrate common chromosomal alterations.
- Discuss potential outcomes of point mutations.
- List and describe three common types of point mutations.
- Discuss consequences of effect-on-function mutations.
- Discuss the significance of germline and somatic mutations.
- Explain why some mutations are harmful and some beneficial.
- Discuss the saying, “Without beneficial mutations, evolution can not occur.”

Introduction

A **mutation** is a change in the DNA or RNA sequence, and many mutations result in new alleles. Some of these changes can be beneficial. In fact, evolution could not take place without the genetic variation that results from mutations. But some mutations are harmful. There are also chromosomal mutations, large changes with dramatic effects.

Causes of Mutation

Is it possible for mutations to occur spontaneously, or does there have to be a cause of the mutation? Well, the answer is that both are possible. A spontaneous mutation can just happen, possibly due to a mistake during DNA replication or transcription. Mutations may also occur during mitosis and meiosis. A mutation caused by an environmental factor, or **mutagen**, is known as an induced mutation. Typical mutagens include chemicals, like those inhaled while smoking, and radiation, such as X-rays, ultraviolet light, and nuclear radiation.

Types of Mutations

In multicellular organisms, mutations can be subdivided into germline mutations, which can be passed on to descendants, and somatic mutations, which cannot be transmitted to the next generation. Germline mutations change the DNA sequence within a sperm or egg cell, and therefore can be inherited . This inherited mutation may result in a class of diseases known as a genetic disease. The mutation may lead to a nonfunctional protein, and the embryo may not develop properly or survive. Somatic mutations may affect the proper functioning of the cell with the mutation. During DNA replication, the mutation will be copied . The two daughter cells formed after cell division will both carry the mutation. This may lead to the development of many cells that do not function optimally, resulting a less than optimal phenotype. Various types of mutations can all have severe effects on the individual. These include point mutations, framehift mutations and chromosomal alterations.

Keep in mind, some mutations may be beneficial or have no effect. Mutations that have no effect will not affect the expression of the gene or the sequence of amino acids in an encoded protein.

Chromosomal Alterations

Chromosomal alterations are large changes in the chromosome structure. They occur when a section of a chromosome breaks and rejoins incorrectly, or does not rejoin at all. Sometimes the segment may join backwards or reattach to another chromosome altogether. These mutations are very serious and usually lethal to the zygote or embryo. If the embryo does survive, the resulting organism is usually sterile and thus, unable to pass along the mutation.

The five types of chromosomal alterations are deletions, duplications, insertions, inversions, and translocations (**Figure** 8.12).

1. **Deletions**: removal of a large chromosomal region, leading to loss of the genes within that region.
2. **Duplications** (or **amplifications**): lead to multiple copies of a chromosomal region, increasing the number of the genes located within that region. Some genes may be duplicated in their entirety.
3. **Insertions**: the addition of material from one chromosome to a nonhomologous chromosome.
4. **Inversions**: reversing the orientation of a chromosomal segment.
5. **Translocations**: interchange of genetic material between nonhomologous chromosomes.

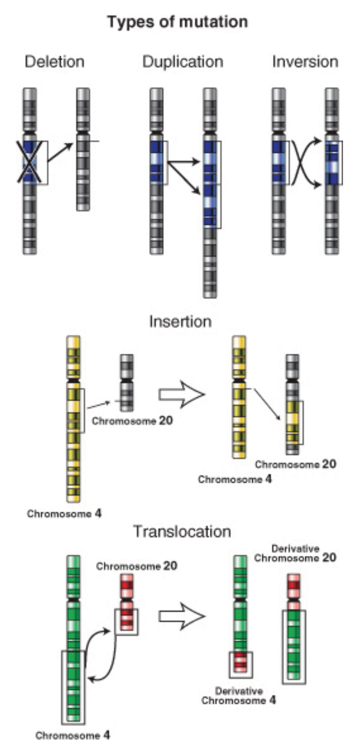

FIGURE 8.14
Figure 8.12 Chromosomal alterations. Deletion: the blue segment has been removed; Duplication: the blue segment has been duplicated; Inversions: the blue segment has been reversed; Insertion: the yellow segment has been removed from chromosome 4 and placed into chromosome 20; Translocation: a green segment from chromosome 4 has been exchanged with a red segment from chromosome 20.

Point Mutations

As the name implies, **point mutations** occur at a single site within the DNA. Lets go back an example:

THE BIG FAT CAT ATE THE RED RAT.

A change at any one position could result in a sequence that does not make sense. Such as:

THE BIG FAT SAT ATE THE RED RAT.

As shown above, point mutations exchange one nucleotide for another and are known as base substitution mutations. These mutations are often caused either by chemicals or by a mistake during DNA replication. A transition

exchanges a purine for a purine (A ↔ G) or a pyrimidine for a pyrimidine, (C ↔ T), and is the most common point mutation.

Deletions and Insertions

As pointed out earlier, a deletion or insertion in the DNA can alter the reading frame. **Deletions** remove one or more nucleotides from the DNA, whereas **insertions** add one or more nucleotides into the DNA. These mutations in the coding region of a gene may also alter splicing of the mRNA (splice site mutation). Mutations which alter the reading frame are known as **frameshift mutations**. **Splice site mutations** and frameshift mutations both can dramatically change the mRNA, altering the final protein product.

Effect-on-Function Mutations

For a cell or organism to maintain homeostasis, the proteins work in a highly defined and regulated manner. It may take just one protein not working correctly to interrupt homeostasis. A protein having more or less activity than normal, or a different activity or function, may be enough to interrupt homeostasis. Mutations that may result in altered function of the gene product or protein are loss-of-function and gain-of-function mutations, as well as dominant negative mutations.

Significance of Mutation

Once again, a mutation is the change in the DNA or RNA sequence. As discussed earlier, in multicellular organisms, mutations can be subdivided into germline mutations and somatic mutations. **Germline mutations** occur in the DNA of sex cells, or gametes, and are therefore potentially very serious. These mutations can be passed to the next generation. **Somatic mutations**, which occur in somatic, or body, cells, cannot be passed to the next generation (offspring). Mutations can be harmful, beneficial, or have no effect. If a mutation does not change the amino acid sequence in a protein, the mutation will have no effect. In fact, the overwhelming majority of mutations have no significant effect, since DNA repair mechanisms are able to mend most of the changes before they become permanent. Furthermore, many organisms have mechanisms for eliminating otherwise permanently mutated somatic cells.

A **gene pool** is the complete set of unique alleles in a species or population. Mutations create variation in the gene pool. Populations with a large gene pool are said to be genetically diverse and very robust. They are able to survive intense times of natural selection against certain phenotypes. During these times of selection, individuals with less favorable phenotypes resulting from deleterious alleles (due to mutations) may be selected against and removed from the population. Concurrently, the more favorable mutations that cause beneficial or advantageous phenotypes tend to accumulate in that population, resulting, over time, in evolution. We will discuss evolution and the genetic effects on evolution in much more detail in a later chapter.

Harmful Mutations

Mutations can result in errors in protein sequence, creating partially or completely non-functional proteins. These can obviously result in harm to the cell and organism. To function correctly and maintain homeostasis, each cell depends on thousands of proteins to all work together to perform the functions of the cell. When a mutation alters a protein that plays a critical role in the cell, the tissue, organ, or organ system may not function properly, resulting in a medical condition. A condition caused by mutations in one or more genes is called a **genetic disorder**, which will be discussed in the next chapter. However, only a small percentage of mutations cause genetic disorders; most have no impact on health. If a mutation does not change the protein sequence or structure, resulting in the same function, it will have no effect on the cell. Often, these mutations are repaired by the DNA repair system of the cell. Each cell has a number of pathways through which enzymes recognize and repair mistakes in DNA (**Figure** 8.13). Because

DNA can be damaged or mutated in many ways, the process of DNA repair is an important way in which the cell protects itself to maintain proper function.

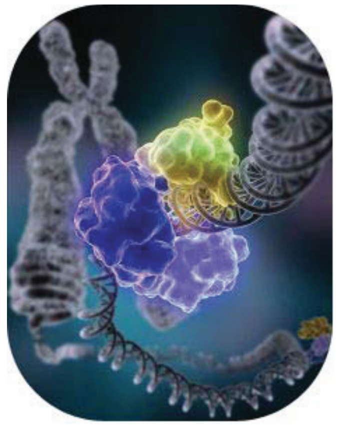

FIGURE 8.15

Figure 8.13 DNA repair. Shown is a model of DNA ligase repairing chromosomal damage.

A mutation present in a germ cell can be passed to the next generation. If the zygote contains the mutation, every cell in the resulting organism will have that mutation. If the mutation results in a disease phenotype, the mutation causes what is called a hereditary disease. These will be discussed in the next chapter. On the other hand, a mutation that is present in a somatic cell of an organism will be present (by DNA replication and mitosis) in all descendants of that cell. If the mutation is present in a gene that is not used in that cell type, the mutation may have no effect. On the other hand, the mutation may lead to a serious medical condition such as cancer. Mutations and cancer will be discussed in the next lesson.

Beneficial Mutations

A very small percentage of all mutations actually have a positive effect. These mutations lead to new versions of proteins that help an organism and its future generations better adapt to changes in their environment. The genetic diversity that results from mutations is essential for evolution to occur. Without genetic diversity, each individual of a species would be the same, and no one particular individual would have an advantage over another. Adaptation and evolution would not be possible. **Beneficial mutations** lead to the survival of the individual best fit to the current environment, which results in evolution. This will be discussed in the evolution chapter.

Mutations and Cancer

During the discussion of the cell cycle, cancer was described as developing due to unregulated cell division. That is, **cancer** is a disease characterized by a population of cells that grow and divide despite the mutations they have. These cancerous cells invade and destroy adjacent tissues, and they may spread throughout the body.

Nearly all cancers are caused by mutations in the DNA of the abnormal cells. These mutations may be due to the effects of **carcinogens**, cancer causing agents such as tobacco smoke, radiation, chemicals, or infectious agents. These carcinogens may act as an environmental "trigger," stimulating the onset of cancer in certain individuals and not others. Do all people who smoke get cancer? No. Complex interactions between carcinogens and an individual's genome may explain why only some people develop cancer after exposure to an environmental trigger and others do not. Do all cancers need an environmental trigger to develop? No. Cancer causing mutations may also result from errors incorporated into the DNA during replication, or they may be inherited. Inherited mutations are present in all cells of the organism.

Several Mutations to Cause Cancer

Typically, a series of several mutations in these genes that activate oncogenes and inactivate tumor suppressor genes is required to transform a normal cell into a cancer cell (**Figure** 8.14). Cells have developed a number of control mechanisms to overcome mutations in proto-oncogenes. Therefore, a cell needs multiple mutations to transform into a cancerous cell. A mutation in one proto-oncogene would not cause cancer, as the effects of the mutation would be masked by the normal control of mitosis and the actions of tumor suppressor genes. Similarly, a mutation in one tumor suppressor gene would not cause cancer either, due to the presence of many "backup" genes that duplicate its functions. It is only when enough proto-oncogenes have mutated into oncogenes and enough tumor suppressor genes have been deactivated that the cancerous transformation can begin. Signals for cell growth overwhelm the signals for growth regulation, and the cell quickly spirals out of control. Often, because many of these genes regulate the processes that prevent most damage to the genes themselves, DNA damage accumulates as one ages.

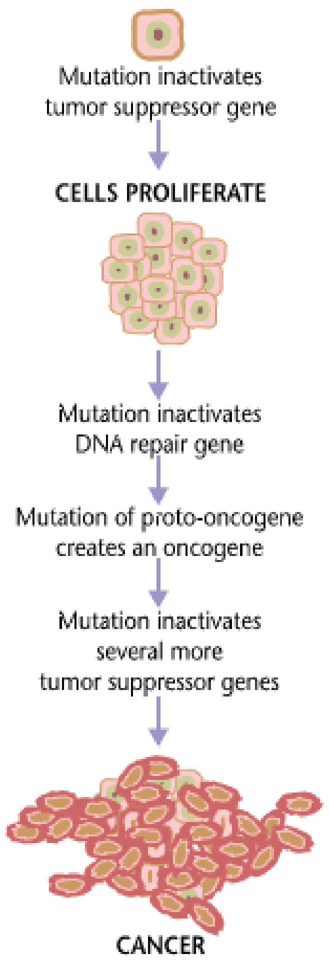

FIGURE 8.16

Cancers are caused by a series of mutations. Each mutation alters the behavior of the cell. In this example, the first mutation inactivates a tumor suppressor gene, the second mutation inactivates a DNA repair gene, the third mutation creates an oncogene, and a fourth mutation inactivates several more tumor suppressor genes, resulting in cancer. It should be noted that it does not necessarily require four or more mutations to lead to cancer.

Lesson Summary

- Mutations may be due to environmental factors (mutagens) or may occur spontaneously.
- Typical mutagens include chemicals, such as those inhaled by smoking, and radiation, like X-rays, ultraviolet light, and nuclear radiation.
- Germline mutations can be passed on to descendants; somatic mutations cannot be transmitted to the next generation.
- Chromosomal alterations are large changes in the chromosome structure. There are 5 types of chromosomal

alterations: deletions, duplications, insertions, inversions, and translocations.
- Point mutations occur at a single site within the DNA; examples of these include silent mutations, missense mutations, and nonsense mutations.
- A deletion or insertion in the DNA can alter the reading frame.
- Loss-of-function and gain-of-function mutations may result in altered function of the gene product or protein.
- Beneficial mutations may accumulate in a population, resulting, over time, in evolution.
- Harmful mutations can result in errors in protein sequence, creating partially or completely non-functional proteins.
- Nearly all cancers are caused by mutations in the DNA of the abnormal cells.
- In non-cancerous cells, proto-oncogenes promote cell growth and mitosis prior to cell division; thus, proto-oncogenes encode proteins needed for normal cellular functions.
- In non-cancerous cells, tumor suppressor genes temporarily discourage cell growth and division to allow cells to finish routine functions, especially DNA repair.
- Mutations in proto-oncogenes and tumor suppressor genes may lead to cancer.
- Usually mutations in multiple genes are necessary to develop cancer.

Review Questions

1. Define mutation.
2. What are some common causes of mutations?
3. List some common types of mutations.
4. Describe some common chromosomal alterations.
5. Discuss potential consequences of point mutations, deletions and insertions.
6. List and describe three common types of point mutations.
7. What are effect-on-function mutations?
8. What is a germline mutation? A somatic mutation?
9. Explain why some mutations are harmful and some beneficial.

Vocabulary Students Need to Know:

Allele

DNA

Replication

Chromosome

Gene

Mutation

Inheritance

Chromosome

RNA

Nucleotide

Adenine

Guanine

Cytosine

Thymine

Codon

Pyrimidines

Purines

Translation

Transcription

Now that we have discussed DNA, protein synthesis and mutations, can you think of a mechanism that allows different cell types to have different proteins?

- What about during development? Why does a developing embryo need different proteins at different times of development?
- We have discussed oncogenes and tumor suppressor genes. Can you think of a specific cellular mechanism in which defects in these genes lead to cancer?

8.4 References

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Chapter 9 Human Genetics - Edited

Chapter Outline

9.1 Lesson 9.1: Human Chromosomes and Genes

Lesson Objectives

- What is a genetic disease?
- What is the human genome?
- Discuss the importance of characterizing the human genome.
- Define autosome and sex-chromosome.
- Discuss the importance of SNPs.
- What is a karyotype?
- Define sex-linked and X-inactivation.

Introduction

As has been previously discussed, genetics is the branch of biology that focuses on heredity. The basics of heredity are similar for all organisms that reproduce sexually: the offspring receive one set of genetic material from one parent and the other set from the other parent. But are there aspects of genetics that are specific for us? Let's find out.

A **genetic disease** is a phenotype due to a mutation in a gene or chromosome. Many of these mutations are present at conception and are therefore in every cell of the body. Mutant alleles may be inherited from one or both parents, resulting in a dominant or recessive hereditary disease. Currently, there are over 4,000 known genetic disorders, with many more phenotypes yet to be identified. Theoretically, every human gene, when disrupted due to a mutation, could result in at least one disease-type phenotype. Genetic diseases are typically diagnosed and treated by a **geneticist**, a medical doctor specializing in these disorders, many of which are extremely rare and difficult to diagnose. Individuals and families with genetic diseases, or suspected genetic diseases, are often counseled by **genetic counselors**, individuals trained in human genetics and counseling. To understand human genetic diseases, you first need to understand human chromosomes and genes.

The Human Genome

What makes each one of us unique? You could argue that the environment plays a role, and it does to some extent. But most would agree that your parents have something to do with your uniqueness. In fact, it is our genes that make each one of us unique – or at least genetically unique. We all have the genes that make us human: the genes for skin and bones, eyes and ears, fingers and toes, and so on. However, we all have different skin colors, different bone sizes, different eye colors and different ear shapes. In fact, even though we have the same genes, the products of these genes work a little differently in most of us. And that is what makes us unique.

The human genome is the genome - all the DNA - of *Homo sapiens*. Humans have about 3 billion bases of information, divided into roughly 20,000 genes, which are spread among non-coding sequences and distributed among 24 distinct chromosomes (22 autosomes plus the X and Y sex chromosomes) (**Figure** 9.1). The **genome** is all of the hereditary information encoded in the DNA, including the genes and non-coding sequences. The Human Genome Project has produced a reference sequence of the human genome. The human genome consists of protein-coding exons, associated introns and regulatory sequences, genes that encode other RNA molecules, and "junk" DNA, regions in which no function as yet been identified.

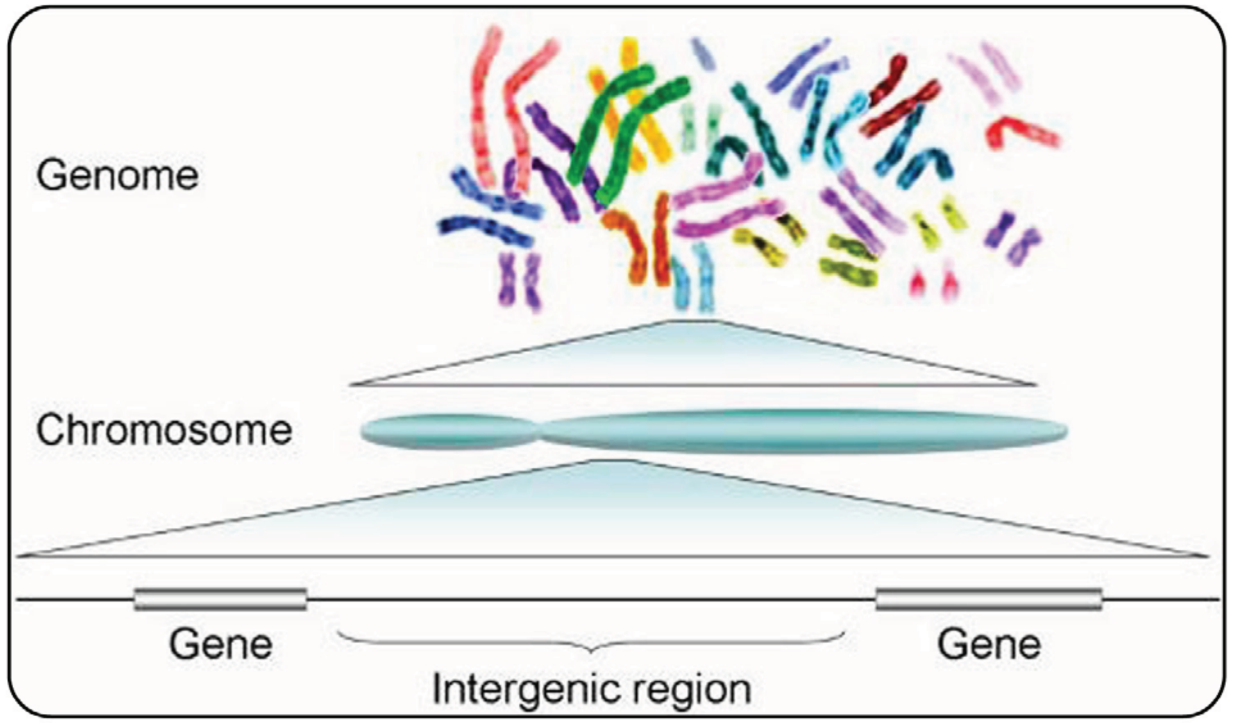

FIGURE 9.1
Figure 9.1 The Human Genome is depicted as the stained chromosomes at the top of the figure. The genome consists of chromosomes, which are composed of genes and other regions of DNA between the genes. Notice that there are 23 pairs of chromosomes.

Chromosomes and Genes

The human genome consists of 24 distinct chromosomes: 22 **autosomal chromosomes** plus the sex-determining X and Y chromosomes. A chromosome is a threadlike molecule of genes and other DNA located in the nucleus of a cell. Different organisms have different numbers of chromosomes. Human somatic cells have 23 chromosome pairs for a total of 46 chromosomes: two copies of the 22 autosomes (one from each parent), plus an X chromosome from the mother and either an X or Y chromosome from the father (**Figure** 9.2).

Linkage

A gene is also said to be linked to a chromosome if it is physically located on that chromosome. For example, a gene (or loci) is said to be linked to the X-chromosome if it is physically located on the X-chromosome. The physical location of a gene is important when analyzing the inheritance patterns of phenotypes due to that gene. The inheritance patterns of phenotypes may be different if the gene is located on a sex chromosome or an autosome.

A crossing-over event during prophase I of meiosis is rare between loci that usually segregate together; these loci will usually be close together on the same chromosome. They are, therefore, said to be linked. Alleles for genes on different chromosomes are not linked; they sort independently (independent assortment) of each other during meiosis.

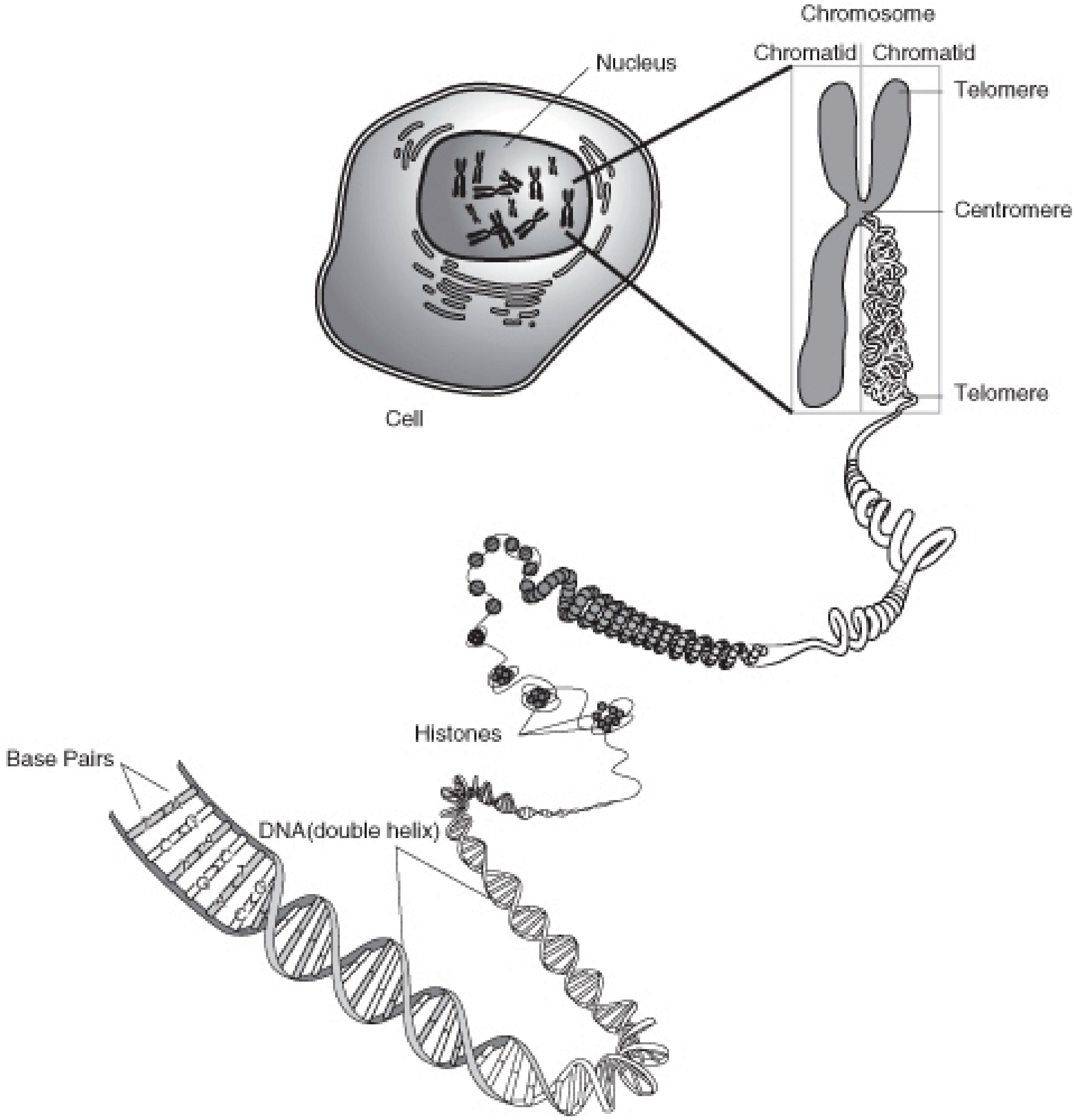

FIGURE 9.2
Figure 9.2 The human genome has 23 pairs of chromosomes located in the nucleus of somatic cells. Each chromosome is composed of genes and other DNA wound around histones (proteins) into a tightly coiled molecule.

Variation

Even though we essentially all have the same genes, the gene products work a little different in all of us, making us unique. That is, the variation within the human genome results in the uniqueness of our species. In fact, genetically

speaking, we are all about 99.9% identical. However, it is this 0.1% variation that results in our physical noticeable differences, as well as traumatic events such as illnesses or congenital deformities. These differences can also be used for societies benefits, such as through forensic DNA analysis. Most studies of this genetic variation focus on small differences, know as **SNPs**, or **single nucleotide polymorphisms**, which are substitutions in individual bases along a chromosome. For example, the single base change from the sequence GGATAACGTCA to GGAAAACGTCA would be a SNP. Although not occurring uniformly, in the human genome, it has been estimated that SNPs occur every 1 in 100 to 1 in 1000 bases.

DNA sequences that repeat a number of times are known as **repetitive sequences** or repetitive elements. For example the sequence CACACACACACACA would be a dinucleotide (2 base) repeat, or the sequence GATCGATCGATCGATCGATC would be a tetranucleotide (4 base) repeat. The genomic loci and length of certain types of repetitive sequences are highly variable from person to person, which is the basis of DNA fingerprinting and DNA paternity testing technologies. Longer repetitive elements are also common in the human genome. Examples of repeat polymorphisms are described in **Table** 9.19.1

TABLE 9.1: **Table 9.1: Repeat Polymorphisms (bp = base pair)**

Dinucleotide	repeats of two bp sequences
Tetranucleotide	repeats of four bp sequences
Microsatellite; Short Tandem Repeats (STRs)	short sequences of 100-200 bp, usually due to repeats of 1-6 bp sequences
Minisatellite	short sequences of 6-10 bp repeats
VNTR: Variable Number of Tandem Repeat	short nucleotide sequence ranging from 14 to 100 nucleotides long, organized into clusters of tandem repeats, usually repeated in the range of between 4 and 40 times per loci

Autosomes and Sex Chromosomes

There are 44 autosomes and 2 sex chromosomes in the human genome, for a total of 46 chromosomes (23 pairs). **Sex chromosomes** specify an organism's genetic sex. Humans can have two different sex chromosomes, one called X and the other Y. Normal females possess two X chromosomes and normal males one X and one Y. An **autosome** is any chromosome other than a sex chromosome. **Figure** 9.3 shows a representation of the 24 different human chromosomes. **Figure** 9.4 shows a karyotype of the human genome. A **karyotype** depicts, usually in a photograph, the chromosomal complement of an individual, including the number of chromosomes and any large chromosomal abnormalities. Karyotypes use chromosomes from the metaphase stage of mitosis.

The 22 autosomes are numbered based on size, with the largest chromosome labeled chromosome 1. These 22 chromosomes occur in homologous pairs in a normal diploid cell, with one of each pair inherited from each parent. The sex of an individual is determined by the sex chromosome within the male gamete. Females are homologous, XX, for the sex chromosomes, whereas males are heterozygous, XY. As all individuals inherit an X chromosome from their mother (females can only produce gametes with an X chromosome), it is the sex chromosome that they inherit from their father that determines their sex.

Both autosomal-linked and sex-linked traits and disorders will be discussed later in this chapter.

Sex-Linked Genes

Sex-linked genes are located on either the X or Y chromosome, though it more commonly refers to genes located on the X-chromosome. For that reason, the genetics of **sex-linked** (or **X-linked**) diseases, disorders due to mutations in genes on the X-chromosome, results in a phenotype usually only seen in males. This will be discussed in the next lesson.

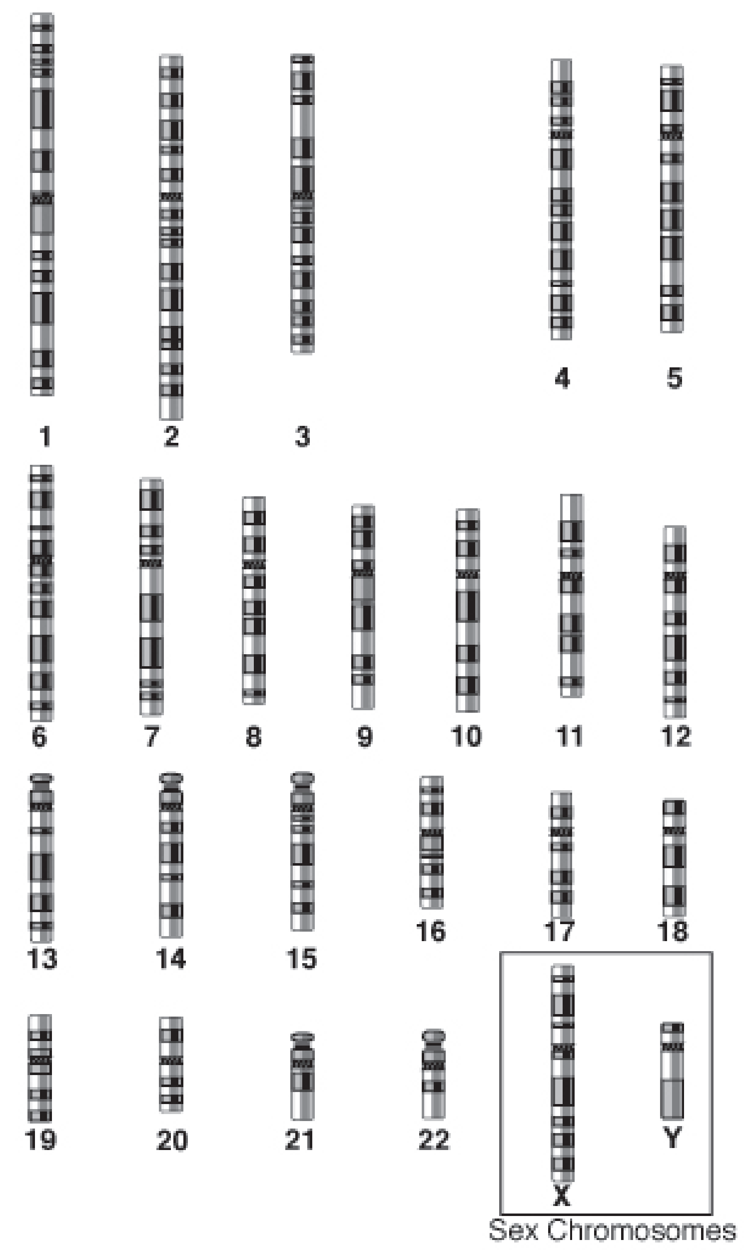

FIGURE 9.3
Figure 9.3 The 24 human chromosomes. The autosomes are numbered 1 - 22, based on size, with chromosome 1 being the largest. The X and Y sex chromosomes are shown in the box.

In humans, the Y chromosome spans 58 million bases and contains about 78 to 86 genes, which code for only 23 distinct proteins, making the Y chromosome one of the smallest chromosomes. The X chromosome, on the other hand, spans more than 153 million bases and represents about 5% of the total DNA in women's cells, 2.5% in men's cells. The X chromosome contains about 2,000 genes, however few, if any, have anything to do with sex determination. The Y chromosome is the sex-determining chromosome in humans and most other mammals. In mammals, it contains the gene **SRY** (sex-determining region Y), which encodes the testes-determining factor and triggers testis development, thus determining sex. It is the presence or absence of the Y chromosome that determines sex.

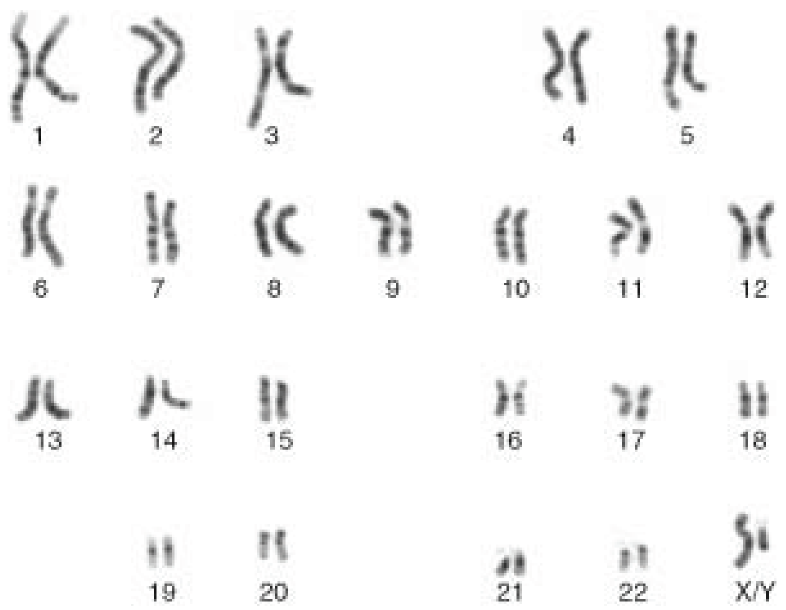

FIGURE 9.4
Figure 9.4 A karyotype of the human genome. Is this from a male or female?

X-Inactivation

Early in embryonic development in females, one of the two X chromosomes is randomly inactivated in nearly all somatic cells. This process, called **X-inactivation**, ensures that females, like males, have only one functional copy of the X chromosome in each cell. X-inactivation creates a Barr body, named after their discover, Murray Barr. The Barr body chromosome is generally considered to be inactive, however there are a small number of genes that remain active and are expressed.

Lesson Summary

- A genetic disease is a phenotype due to a mutation in a gene or chromosome.
- Many of these mutations are present at conception, and are therefore in every cell of the body.
- Mutant alleles may be inherited from one of both parents, resulting in a dominant or recessive hereditary disease.
- Currently there are over 4,000 known genetic disorders, with many more phenotypes yet to be identified.
- The genome refers to all the DNA of a particular species.
- The human genome consists of 24 distinct chromosomes: 22 autosomal chromosomes, plus the sex-determining X and Y chromosomes.
- Linkage refers to particular genetic loci or alleles inherited together, suggesting that they are physically on the same chromosome, and located close together on that chromosome.
- The variation within the human genome results in the uniqueness of our species.
- There are 44 autosomes and 2 sex chromosomes in the human genome, for a total of 46 chromosomes.
- Sex chromosomes specify an organism's genetic sex. Humans have two different sex chromosomes, one called X and the other Y.
- Sex-linked genes are located on either the X or Y chromosome, though it more commonly refers to genes located on the X-chromosome.
- Early in embryonic development in females, one of the two X chromosomes is randomly inactivated in nearly all somatic cells. This process is called X-inactivation.

Review Questions

1. What is a genetic disease?
2. Discuss the main difference between autosomal and sex-linked.
3. Why is variation within the human genome important?
4. Why is it more common for males to have X-linked disorders?
5. Describe how a mutation can lead to a genetic disease.
6. Discuss how a new mutation can become a new dominant allele.
7. How are autosomal traits usually inherited? Give examples of traits.
8. How are genetic diseases usually inherited? Are there exceptions? Research examples.

Points to Consider

- How are traits inherited? How about the inheritance of genetic disorders? Are inheritance patterns of traits and disorders similar?
- Could simple Mendelian inheritance account for such complex traits with vast phenotypic variation such as height or skin color? What do you think?

9.2 Lesson 9.2: Human Inheritance

Lesson Objectives

- Describe the difference between a genetic trait and a genetic disease/disorder.
- Define the various modes of inheritance, focusing on the differences between autosomal and sex-linked.
- Gives examples of dominant and recessive genetic disorders.
- Discuss the inheritance of sex-linked traits.
- Discuss complex inheritance patterns.
- Define codominant alleles and give examples.
- Define incomplete dominance.
- Give examples of multiple allele traits.
- Discuss how a trisomy condition may be detected.
- What is Down syndrome?
- List some examples of phenotypes due to abnormal numbers of sex chromosomes.
- Discuss the importance of gene therapy.
- Describe the most common method of gene therapy.

Introduction

What is a genetic trait? Is a genetic disease a trait? The answer to these questions may be debated, but a genetic trait is a characteristic of you encoded in your DNA. Could you say that a genetic disease is encoded in your DNA? Well, by definition, yes you can.

How are traits inherited? Do different traits have different patterns of inheritance? Is it as simple as a one allele – one phenotype relationship? Or is it more complex? Is there a difference if the gene is located on an autosome or a sex chromosome? Can there be traits due to multiple genes? The answer to all of the above questions is a resounding 'sometimes.' Sometimes it is as simple as a one allele – one phenotype relationship, sometimes it is more complex. Sometimes there is a difference depending on the location of the gene. Sometimes traits can be due to multiple genes. Human genetics is an exciting aspect of biology and medicine; an aspect of biology that is extremely important to our health and well being.

Autosomal and Sex-Linked Traits: Mutations and Genetic Disorders

Autosomal vs. sex-linked. In terms of genetics, is the location of a gene or trait an important piece of information? Does it make a difference if the gene is located on a sex chromosome or an autosome? It might. Remember from lesson 9.1 that sex chromosomes determine an organism's sex, so the autosomes are the other chromosomes. Autosomal-linked traits are due to genes on the **autosomes**; **sex-linked traits** are due to genes located on the **sex chromosomes**.

What is the difference between a trait and a genetic disorder? Could a disorder be considered a trait? We tend to think of traits as hair color or skin color and disorders as something that is bad for you. But in terms of genetics, a genetic disorder is a trait. Both may be due to your genes.

Simple Dominant Heredity

How are traits due to genes on autosomes inherited? Autosomal traits due to the effects of one gene are usually inherited in a simple Mendelian pattern. That is, they can be either dominant or recessive. In humans, whereas many genetic disorders are inherited in a recessive manner, simple dominant inheritance accounts for many of a person's physical characteristics, such as chin, earlobe, hairline and thumb shape. For example, having earlobes that are attached to the head is a recessive trait, whereas heterozygous and homozygous dominant individuals have freely hanging earlobes. If you have a cleft chin, a pointed frontal hairline (called a widow's peak), or a hitchhiker's thumb, you have inherited the dominant allele for each characteristic from at least one of your parents. Other dominant traits include the presence of hair on the middle section of your fingers, thick lips, and almond-shaped eyes. A widow's peak and earlobe shape are displayed in **Figure** 9.5 and **Figure** 9.6.

FIGURE 9.5
Figure 9.5 A young woman with a widow's peak.

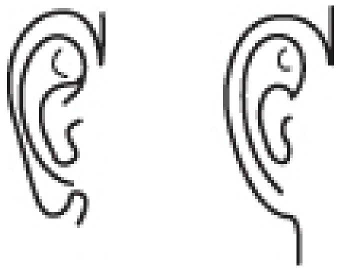

FIGURE 9.6
Figure 9.6 A diagram showing free (left) and attached (right) earlobes. Attached earlobes is a recessive trait.

Mutations and Genetic Disorders

Mutations, changes in the DNA or RNA sequence, can have significant phenotypic effects or no effects. We have previously discussed various types of mutations. Now, let's discuss the outcomes of some of those mutations. As mentioned at the beginning of this chapter, a genetic disorder is a condition caused by abnormalities, such as mutations, in your genes or chromosomes. Genetic disorders are usually present from conception. These disorders include chromosomal abnormalities, in which the individual has too few or too many chromosomes or chromosomes with large alterations, or diseases due to a mutation in a specific gene. These defective genes are usually inherited from the parents, hence the term hereditary disease or genetic disorder. Genetic disorders can be inherited in a dominant or recessive manner (**Figure** 9.7 and **Figure** 9.8). Recessive disorders require the inheritance of a defective gene from each parent. The parents are usually unaffected and are healthy carriers of the defective gene.

How can you, or a geneticist, determine the inheritance pattern of a phenotype? A **pedigree**, which is essentially a representation of genetic inheritance, is helpful. A pedigree is a chart, much like a family tree, which shows all of the

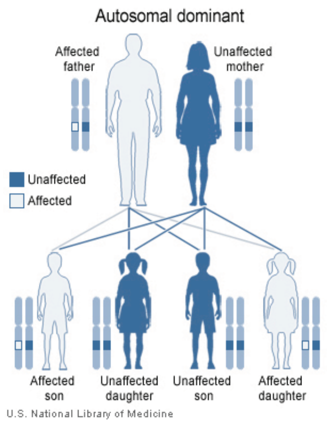

FIGURE 9.7
Figure 9.7 Autosomal Dominant Inheritance. Only one

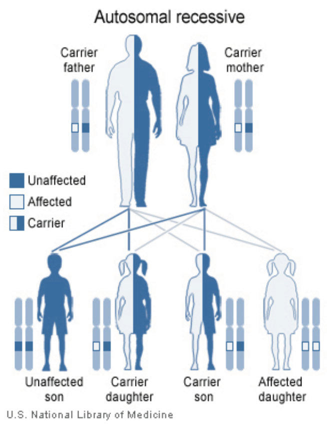

FIGURE 9.8
Figure 9.8 Autosomal Recessive inheritance. For a genetic disease inherited in this manner, two mutant alleles are necessary to result in the phenotype. Tay-Sachs Disease (discussed later) is an example of a recessive disorder. Notice that both parents are unaffected carriers of the mutant allele. These unaffected carriers allow the allele to be maintained in the gene pool - the complete set of a population's genes. Even if the allele is lethal in the homozygous recessive condition, the allele will be maintained through heterozygous individuals.

known individuals within a family with a particular phenotype (**Table** 9.2 9.2Autosomal and Sex-linked Inheritance Patterns). Pedigrees have been discussed in the chapter titled *Mendelian Genetics*. Examples of autosomally inherited disorders include cystic fibrosis, Tay-Sachs disease, phenylketonuria, and achondroplasia.

TABLE 9.2: Table 9.2: Autosomal and Sex-linked Inheritance Patterns

Inheritance Pattern	Description	Example
Autosomal Dominant	Only one mutated allele is needed for a person to be affected by an **autosomal dominant disorder**. Each affected person usually has one affected parent. There is a 50% chance that a child will inherit the mutated gene.	Huntingtons disease, Achondroplasia, Neurofibromatosis 1, Marfan Syndrome, Hereditary nonpolyposis colorectal cancer
Autosomal Recessive	Both copies of the gene must be mutated for a person to be affected by an **autosomal recessive disorder**. An affected person usually has unaffected parents who each carry a single copy of the mutated gene (and are referred to as carriers).	Cystic fibrosis, Sickle cell anemia, Tay-Sachs disease, Spinal muscular atrophy

TABLE 9.2: (continued)

Inheritance Pattern	Description	Example
X-linked Dominant	**X-linked dominant disorders** are caused by mutations in genes on the X chromosome. Only a few disorders have this inheritance pattern.	
X-linked Recessive	**X-linked recessive disorders** are also caused by mutations in genes on the X chromosome. Males are more frequently affected than females. The sons of a man with an X-linked recessive disorder will not be affected, and his daughters will carry one copy of the mutated gene. A woman who carries an X-linked recessive disorder has a 50% chance of having sons who are affected and a 50% chance of having daughters who carry one copy of the mutated gene.	Hemophilia A, Duchenne muscular dystrophy, Color blindness
Y-Linked	**Y-linked disorders** are caused by mutations on the Y chromosome. Only males can get them, and all of the sons of an affected father are affected. Y-linked disorders only cause infertility, and may be circumvented with the help of some fertility treatments.	Male Infertility

Cystic Fibrosis

Cystic fibrosis (CF) is a recessive inheritable disorder caused by a mutation in a gene called the cystic fibrosis transmembrane conductance regulator (CFTR). The product of this gene is a chloride ion channel important in creating sweat, digestive juices, and mucus. Although most people without CF have two working copies of the CFTR gene, only one is needed to prevent cystic fibrosis. CF develops when individuals have a mutation in both copies of the gene, such that neither gene product works normally. CF is one of the most common life shortening diseases. Diagnosis is usually made in childhood. In the United States, approximately 1 in 3,900 children is born with CF (**Figure** 9.9). One in 22 people of European descent are carriers of a mutated CFTR gene. CF mainly affects the lungs and digestive system, causing difficulty breathing due to thick mucus production, progressive disability, and for some individuals, premature death.

Individuals can be diagnosed prior to birth by genetic testing. Because development of CF in the fetus requires each parent to pass on a mutated copy of the CFTR gene and because CF testing is expensive, testing is often initially performed on just one parent. If that parent is found to be a carrier of a CFTR gene mutation, the other parent is then tested to calculate the risk that their children will have CF. CF can result from more than a thousand different mutations; currently it is not possible to test for each one. As new DNA testing methodologies are developed, testing for more mutations will become more common and less expensive. Testing analyzes DNA for the most common mutations, such as a deletion of amino acid 508 (phenylalenine, also known as ΔF508). If a family has a known uncommon mutation, specific screening for that mutation can be performed. However, it must be noted that because there may be other not yet identified mutations that result in CF, and as not all known mutations are found on current

tests, a negative screen does not guarantee that a child will not have CF.

FIGURE 9.9

Figure 9.9 A young cystic fibrosis patient undergoing breathing treatment. Cystic fibrosis is a recessively inherited genetic disorder.

Tay-Scahs Disease

Tay-Sachs disease is a genetic disorder that is fatal in its most common variant, known as Infantile Tay-Sachs disease. Tay-Sachs is an autosomal recessive disorder, requiring the inheritance of a defective gene from each parent. The disease results from the accumulation of harmful quantities of fat in the nerve cells of the brain. Tay-Sachs results from mutations in the HEXA gene located on chromosome 15, which encodes the alpha-subunit of the lysosomal enzyme beta-N-acetylhexosaminidase A, which normally breaks down the fat. More than 90 mutations, including substitutions, insertions, deletions, splice site mutations, and other more complex patterns have been characterized in this gene, and new mutations are still being reported. Each of these mutations alters the protein product, inhibiting the function of the enzyme.

Tay-Sachs disease is a rare disease. Unaffected carriers of a Tay-Sachs allele may not know they have the allele. Other autosomal disorders such as cystic fibrosis and sickle cell anemia are far more common. The importance of Tay-Sachs lies in the fact that an inexpensive enzyme assay test was developed. The automation of this analysis has provided one of the first "mass screening" tools in medical genetics. Two unaffected carriers can have a child homozygous for a Tay-Sachs allele, resulting, currently, in a lethal phenotype. Tay-Sachs alleles are maintained in a population through these unknowing heterozygous carriers.

The analysis and screening for Tay-Sachs has became a research and public health model for understanding and preventing all autosomal genetic disorders. Another genetic disease that is easily analyzed in phenylketonuria.

Phenylketonuria

Phenylketonuria (PKU) is an autosomal recessive genetic disorder characterized the inability to metabolize the amino acid phenylalanine. PKU is due to a deficiency in the enzyme phenylalanine hydroxylase (PAH). When PAH is deficient, phenylalanine accumulates and is converted into phenylketones, which can be detected in the urine. Left untreated, this condition can cause problems with brain development, leading to progressive mental retardation and seizures. However, PKU can be treated with a specific diet, one low in phenylalanine. A diet low in phenylalanine and high in tyrosine can bring about a nearly total cure.

The incidence of PKU is about 1 in 15,000 live births. In the United States PKU is screened at birth as part of a national biochemical screening program, for every baby born in a hospital. Babies born at home may not be screened. If PKU is diagnosed early enough, an affected newborn can grow up with normal brain development, but only by eating a special diet low in phenylalanine for the rest of his or her life. In essence, this is a protein-free diet. This requires severely restricting or eliminating foods high in protein content (containing phenylalanine), such as breast milk, meat, chicken, fish, nuts, cheese and other dairy products. Starchy foods such as potatoes, bread, pasta, and corn must also be monitored. Many diet foods and diet soft drinks that contain the sweetener aspartame must

also be avoided, as aspartame consists of two amino acids: phenylalanine and aspartic acid. Supplementary infant formulas are used in these patients to provide the amino acids and other necessary nutrients that would otherwise be lacking in their diet. Since phenylalanine is required for the synthesis of many proteins, it is necessary to have some of this amino acid, but levels must be strictly controlled. In addition, tyrosine, which is normally derived from phenylalanine, must also be supplemented.

Achondroplasia

Whereas cystic fibrosis, Tay-Sachs, and phenylketonuria are all autosomal recessive disorders, **achondroplasia** is an autosomal dominant disorder. Achondroplasia is the most common cause of dwarfism. Achondroplasia is a result of an autosomal dominant mutation in the fibroblast growth factor receptor gene 3 (FGFR3), which causes an abnormality of cartilage formation. FGFR3 normally has a negative regulatory effect on bone growth. In achondroplasia, the mutated form of the receptor is constitutively active (constantly "turned on") and this leads to severely shortened bones. Individuals with achondroplasia are heterozygous for the mutation (one mutant copy, one normal copy). Homozygous for the achondroplasia mutation is lethal prior to birth or shortly after birth.

For autosomal dominant disorders, a person with the disorder has a 50% chance of passing on the gene to their offspring. For achondroplasia, this means there will be a 50% chance that each child will have achondroplasia. Since two copies are fatal, if two people with achondroplasia have a child, there is a 25% chance of the child dying shortly after birth, a 50% chance the child will have achondroplasia, and a 25% chance the child will have a normal phenotype. However, in 3 out of 4 cases, people with achondroplasia are born to parents who don't have the condition. This is the result of a new mutation. New achondroplasis mutations are associated with increasing paternal age (over 35 years). Studies have demonstrated that new gene mutations are exclusively inherited from the father and occur during spermatogenesis. More than 98% of achondroplasia is caused by a G to A point mutation at nucleotide 1138 of the FGFR3 gene, which causes a glycine to arginine substitution. This makes this particular nucleotide one of the most, if not the most, mutable base in the human genome.

Sex-Linked Traits

Traits controlled by genes located on the sex chromosomes (X and Y) are called sex-linked traits (**Figure** 9.10). Remember, females have two X chromosomes and males have a X and a Y chromosome. Therefore, any recessive allele on the X chromosome of a male will not be masked by a dominant allele. X-linked traits include the hemophilia and color blindness. Hemophilia is the name of a family of hereditary genetic illnesses that impair the body's ability to control coagulation (clotting of blood). Color Blindness, or color vision deficiency, in humans is the inability to perceive differences between some or all colors that other people can distinguish.

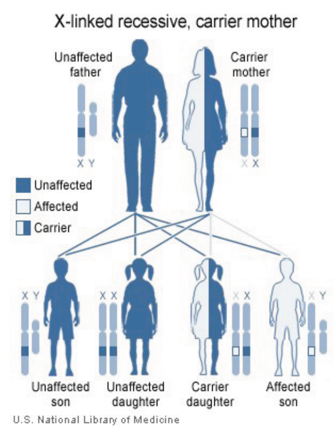

FIGURE 9.10

Figure 9.10 X-linked recessive inheritance. As boys have only one X-chromosome, if they inherit the mutant allele from their mother, they will possess the phenotype that results from that allele.

Hemophilia is a group of diseases in which blood does not clot normally. Factors in blood are involved in clotting. Hemophiliacs lacking the normal Factor VIII are said to have Hemophilia A, the most common form. England's Queen Victoria was a carrier for this disease. The allele was passed to two of her daughters and one son. Since royal families in Europe commonly intermarried, the allele spread, and may have contributed to the downfall of the Russian monarchy.

Genetic red-green color blindness affects men much more often than women, because the genes for the red and green color receptors are located on the X chromosome. Females are red-green color blind only if both of their X chromosomes carry the defective gene, whereas males are color blind if their single X chromosome carries the defective gene. As males have only the one X-chromosome, the gene for red-green color blindness is transmitted from a color blind male to all his daughters, who are usually heterozygous carriers and therefore unaffected. Subsequently, this carrier woman has a fifty percent chance of passing on a X chromosome with a defective gene to each of her male offspring. The sons of an affected male will not inherit the trait from him, since they receive his Y chromosome and not his X chromosome. Should an affected male have children with a carrier or colorblind woman, their daughters may be colorblind by inheriting a X chromosome with the mutant gene from each parent.

Muscular dystrophy is a term encompassing a variety of muscle wasting diseases. The most common type, **Duchenne Muscular Dystrophy** (DMD), affects cardiac and skeletal muscle, as well as some mental functions. DMD is an X-linked recessive disorder occurring in 1 in 3,500 newborns. Most affected individuals die before their 20th birthday.

Complex Traits

Codominance

Codominance is when two alleles are both expressed in the heterozygous individual; that is, they both affect the phenotype in separate and distinguishable ways (**Figure** 9.11). The A, B alleles of the ABO blood group system are a classic example, and these have been discussed in the chapter titled *Mendelian Genetics.* The A and B alleles are codominant with each other. When a person has both an A and a B allele, the person has type AB blood. When two persons with AB blood type have children, the children can be type A, type B, or type AB. There is a 1A:2AB:1B phenotype ratio instead of the 3:1 phenotype ratio found when one allele is dominant and the other is recessive.

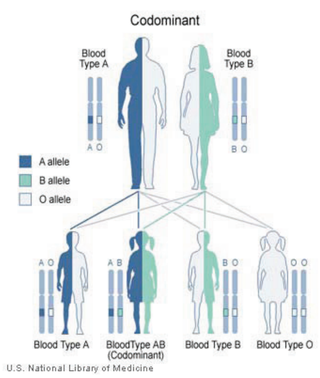

FIGURE 9.11

Figure 9.11 Codominant Inheritance. The A and B alleles are codominant. An AB heterozygous individual has type AB blood.

Incomplete Dominance

Incomplete dominance is seen in heterozygous individuals with an intermediate phenotype. For example, if Mendel had ever observed a medium stem length plant when a tall and short plant were crossed, that would have suggested incomplete dominance. In incomplete dominant situations, the phenotype expression is dependent on the dosage of

the genes. Two copies of the gene result in full expression, while only one copy produces partial expression and an intermediate phenotype.

Multiple-Allele Traits

Traits controlled by more than two alleles have multiple alleles. Theoretically, any base change will result in a new allele. In fact, within the human population, it may be safe to say that most human genes have more than 2 alleles. Whereas, we think of base changes, or mutations, as resulting in a new phenotype or disease, many base changes result in alleles that do not cause significant change in phenotypes. This is common in collagen genes, for example. The best characterized example of multiple alleles in humans is the ABO blood groups, discussed in the chapter titled *Mendelian Genetics*. Multiple alleles resulting in multiple phenotypes are not uncommon.

Polygenic Traits

Polygenic traits are due to the actions of more than one gene and often, their interaction with the environment. These usually result in a measurable range in phenotype, such as height, eye color or skin color. These are known as multifactoral or quantitative characteristics. Polygenic inheritance results in an additive effect of the genes on a single phenotype.

Skin color is a polygenic trait and obviously demonstrates quantitative characteristics. A number of genes factor into determining a person's natural skin color, so modifying only one of those genes changes the color only slightly. It is currently thought that at least three separately inherited genes contribute to skin pigmentation. Let's call these three genes A, B, and C. A, B, and C are incompletely dominant to a, b, and c, with A, B, and C each contributing a "unit of darkness" to the phenotype. Therefore an AABBCC individual is very dark, darker than an AaBbCc individual, and much darker than a aabbcc individual. A person may have as many as 6 "dark units" to as few as no "dark units," and any combination in between. This will result in a phenotypic spectrum of color gradation.

Many disorders with genetic components are polygenic, including autism, certain cancers, diabetes and numerous others. Most phenotypic characteristics are the result of the interaction of multiple genes. The environment plays a significant role in many of these phenotypes. But what happens when multiple genes are either missing or duplicated?

Changes in Chromosome Number

So far we have focused on traits due to one gene or several genes. But what about many genes? What would happen if an entire chromosome were missing or duplicated? What if a human had only 45 chromosomes? Or 47? This real possibility is usually due to mistakes during meiosis; the chromosomes do not fully separate from each other during sperm or egg formation. Specifically, **nondisjunction** is the failure of replicated chromosomes to separate during anaphase II. If a zygote forms from a gamete lacking a chromosome, a viable embryo cannot be produced. Most human abnormal chromosome numbers result in the death of the developing embryo, often before a woman even realizes she is pregnant. Occasionally, a zygote with an extra chromosome can become a viable embryo and develop.

Trisomy is a state where humans have an extra autosome. That is, they have three of a particular chromosome instead of two. For example, trisomy 18 results from an extra chromosome 18, resulting in 47 total chromosomes. To identify the chromosome number (including an abnormal number), a sample of cells is removed from an individual or developing fetus. Metaphase chromosomes are photographed and a karyotype is produced. A karyotype will display any abnormalities in chromosome number or large chromosomal rearrangements. Trisomy 8, 9, 12, 13, 16, 18, and 21 have been identified in humans. Trisomy 16 is the most common trisomy in humans, occurring in more than 1% of pregnancies. This condition, however, usually results in spontaneous miscarriage in the first trimester. The most common trisomy in viable births is **Trisomy 21**. (**Figure** 9.12)

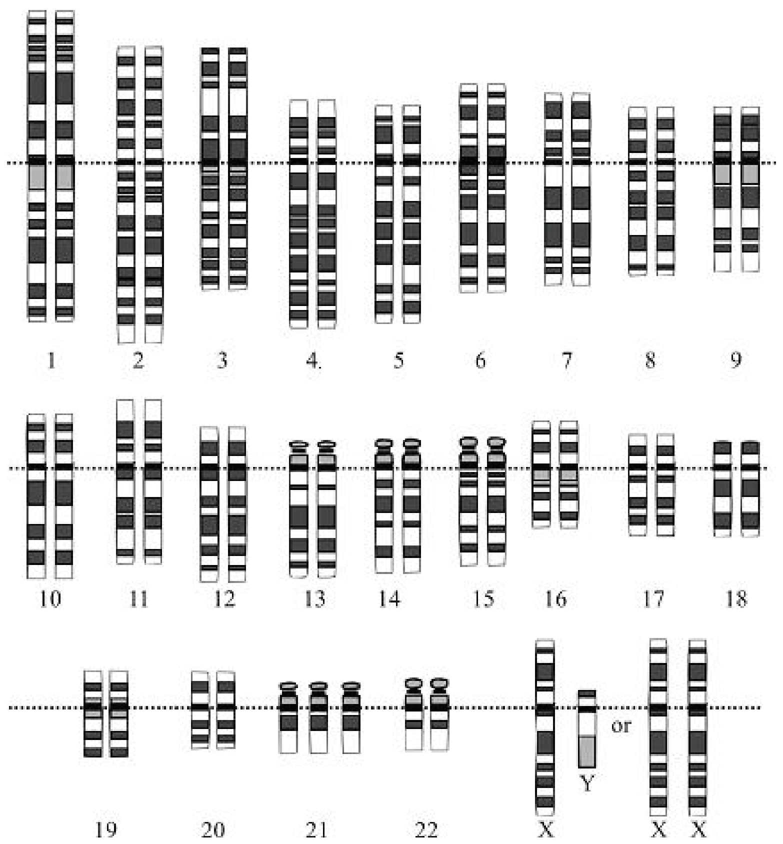

FIGURE 9.12
Figure 9.12 Trisomy 21 (Down Syndrome) Karyotype. Note the extra chromosome 21.

Trisomy 21: Down Syndrome

One of the most common chromosome abnormalities is Down syndrome, due to nondisjunction of chromosome 21 resulting in an extra complete chromosome 21, or part of chromosome 21 (**Figure** 9.12). Down syndrome is the only autosomal trisomy where an affected individual may survive to adulthood. Individuals with Down syndrome often have some degree of mental retardation, some impairment of physical growth, and a specific facial appearance. With proper assistance, individuals with Down syndrome can become successful, contributing members of society (**Figure** 9.13). The incidence of Down syndrome increases with maternal age.

FIGURE 9.13
Figure 9.13 Child with Down syndrome, exhibiting characteristic facial appearance.

Abnormal Numbers of Sex Chromosomes

What about when a person has more than 2 Y chromosomes, or more than 2 X chromosomes? Or a female with only one X chromosome? Sex-chromosome abnormalities may be caused by nondisjunction of one or more sex chromosomes. Many conditions are known in which there are an abnormal number of sex chromosomes. An X chromosome may be missing (XO), or there may be an extra one (XXX or XXY). There may also be an extra Y chromosome (XYY). Any combination of X and Y chromosomes, as long as there is a Y chromosome, will produce a male (up to XXXXY). These individuals can lead relatively normal lives, but they cannot have children. They may also have some degree of mental retardation. These syndromes include Klinefelter's syndrome, Turner syndrome and trisomy X.

Klinefelter's syndrome is caused by the presence of one or more extra copies of the X chromosome in a male's cells. Extra genetic material from the X chromosome interferes with male sexual development, preventing the testicles from functioning normally and reducing the levels of testosterone. Triple X syndrome (**trisomy X**) results from an extra copy of the X chromosome in each of a female's cells. Females with trisomy X have a lower IQ than their siblings. Turner syndrome results when each of a female's cells has one normal X chromosome and the other sex chromosome is missing or altered. The missing genetic material affects development and causes the characteristic features of the condition, including short stature and infertility.

Diagnosis and Treatment of Genetic Disorders

If someone has a rare genetic disease in her family, can she still have a baby? Is she predisposed to pass that phenotype along to her child? These are questions for a professional trained in human genetics. A geneticist and **genetic counselor** are usually involved in the diagnosis and treatment of human genetic disorders. Families with a genetic disease are referred to a genetic counselor, especially when they wish to determine a baby's likelihood of inheriting a genetic disease.

Prenatal Diagnosis

"Is it possible to test the developing baby for potential genetic problems? Do you need to remove some of the baby's DNA? How do you do that?" These questions are appropriate for a geneticist. Sometimes, to make sure the baby is developing properly, prenatal diagnosis is necessary. **Prenatal diagnosis** refers to the diagnosis of a disease or condition before the baby is born. The reason for prenatal diagnosis is to detect birth defects such as neural tube defects, chromosome abnormalities, genetic diseases and other conditions. It can also be used to determine the sex of the unborn baby, though this can usually be determined by an ultrasonography (ultrasound).

Diagnostic prenatal testing can be by invasive methods or non-invasive methods. Non-invasive methods are much less risky to the patient. Non-invasive methods can only evaluate the risk of a condition and cannot actually determine if the fetus has a condition. Non-invasive techniques include examinations of the mother's womb through ultrasonography and analysis of maternal serum. If an abnormality is indicated by a non-invasive procedure, a more invasive technique may be employed to gather more information. **Amniocentesis** and **chorionic villus sampling** (CVS) are invasive procedures. These involve probes or needles that are inserted into the placenta. Amniocentesis can be done from about 14 weeks up to about 20 weeks of the pregnancy and CVS can be done earlier, between 9.5 and 12.5 weeks, but is slightly more risky to the unborn child.

Gene Therapy

So, how do you treat genetic disorders? If medically possible, each manifestation can be treated separately. But is there a way to use genetics to treat the root cause of the disease – that is, to fix the mistake in the DNA?

Gene therapy is the insertion of a new gene into an individual's cells and tissues to treat a disease, replacing a mutant disease-causing allele with a normal, non-mutant allele. Although the technology is still in its early stages of development, it has been used with some success.

There are a number of mechanisms used to replace or repair a defective gene in gene therapy.

- A normal gene may be inserted into a nonspecific location within the genome to replace a nonfunctional gene. This approach is most common.
- An abnormal gene could be replaced by a normal gene through homologous recombination.
- The abnormal gene could be repaired through selective reverse mutation, which returns the gene to its normal, non-mutant state.
- The regulation (the degree to which a gene is turned on or off) of a particular gene could be altered.

As stated above, the most common gene therapy approach is to replace a disease-causing allele with a normal allele. To deliver the new allele to the appropriate cells, a carrier, called a vector, must be used. Currently, the most common type of vectors are viruses that have been genetically altered to carry normal human DNA, and not to result in any phenotypes associated with the virus. As viruses have evolved a robust method of delivering their viral genes to human cells, scientists have tried to develop (and are continuing to develop) methods to take advantage of this process, and have these vectors insert human DNA into target cells. Scientists have manipulated the viral genome to remove disease-causing genes and insert therapeutic human genes (**Figure** 9.14). For obvious reasons, this is currently a field of intense biomedical research.

A patient's target cells, such as liver or lung cells are infected with the genetically altered virus. The vector then unloads its genetic material containing the therapeutic human gene into the target cell. The generation of a functional protein product from the therapeutic gene should restore the target cell to a normally functioning phenotype. To date, this process has had limited success, but who can say what will happen in the future.

Lesson Summary

- In humans, whereas many genetic disorders are inherited in a recessive manner, simple dominant inheritance accounts for many of a person's physical characteristics.
- Genetic diseases may also be dominantly inherited, such as with achondroplasia.
- Genetic diseases may be due to specific mutations within a gene or to large chromosomal abnormalities.
- Traits controlled by genes located on the sex chromosomes (X and Y) are called sex-linked traits.
- Any recessive allele on the X chromosome of a male will not be masked by a dominant allele.
- Codominance is when two alleles are both expressed in the heterozygous individual.
- Incomplete dominance is seen in heterozygous individuals with an intermediate phenotype.
- Traits controlled by more than two alleles have multiple alleles.
- Polygenic traits are due to the actions of more than one gene and often, their interaction with the environment.
- Trisomy is a state where humans have an extra autosome; they have three of a particular chromosome instead of two.
- The most common trisomy in viable births is Trisomy 21 (Down Syndrome).
- Prenatal diagnosis refers to the diagnosis of a disease or condition before the baby is born.
- Amniocentesis and chorionic villus sampling are invasive methods involved in prenatal diagnosis.
- Gene therapy is the insertion of a new gene into an individual's cells and tissues to treat a disease, replacing a mutant disease-causing allele with a normal, non-mutant allele.

Review Questions

1. What is a genetic disease?
2. Discuss the main difference between autosomal and sex-linked.

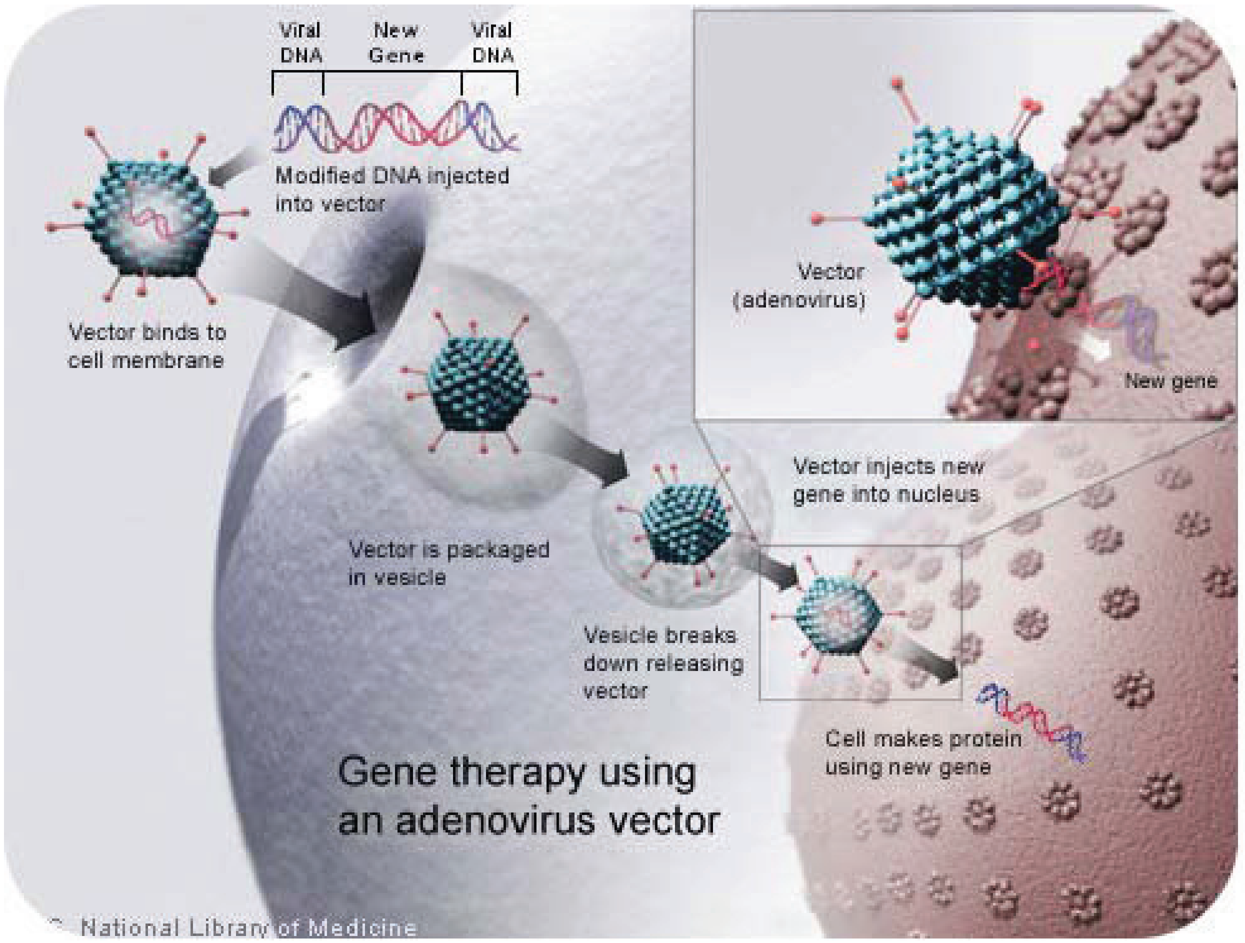

FIGURE 9.14

Figure 9.14 Gene Therapy using a viral vector. The new gene is inserted into the viral genome, the virus binds to the cell membrane and enters the cell by endocytosis. The viral genome, containing the new gene is injected into the cell nucleus, where the viral DNA is transcribed, starting the process of protein synthesis.

3. Why is variation within the human genome important?
4. Why is it more common for males to have X-linked disorders?
5. Describe how a mutation can lead to a genetic disease.
6. Discuss how a new mutation can become a new dominant allele.
7. How are autosomal traits usually inherited? Give examples of traits.
8. How are genetic diseases usually inherited? Are there exceptions? Give examples.
9. Discuss the difference between codominance and incomplete dominance. Give examples.
10. What is meant by trisomy? How can trisomy phenotypes be detected?
11. What is the most common viable trisomy disorder?
12. List conditions involving an abnormal number of sex chromosomes.
13. What is gene therapy?
14. Describe the most common approach to gene therapy.

Vocabulary Students Need to Learn:

Mutation

Autosome

Sex Chromosomes

Sex-Linked traits

Codominance

Incomplete Dominance

Karyotype

Recessive Disorder

Dominant Disorder

Genetics

Genetic Disorders

Gene splicing

Gene Therapy

In this chapter, we discussed human genetics as involved in human health. In the next chapter, we will discuss biotechnology. With gene therapy, we can see how biotechnology will play a significant role in society's future.

- Can you speculate on the role of biotechnology in our future?
- What other roles for biotechnology do you envision?
- Why is biotechnology important?

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Chapter 10 Evidence of Evolution which leads to Diversity of Life

Chapter Outline

10.1 Evolution by Natural Selection

Lesson Objectives

- Cite evidence for changes in populations over time and use concepts of evolution to explain these changes.
- Understand that inherited traits, such as the basic color of skin or a person's bone structure, are passed on to future generations.
- Understand that acquired traits, such as a tan or being good at soccer, are not passed on to future generations (they are not inherited).
- Understand that evolution is change of an inherited trait in a population over many generations, such as the change of the color of moths living on an island over many generations.
- Understand that natural selection means that organisms with traits that help them survive in their environment are more likely to survive than organisms without that beneficial trait.
- Understand how evolution explains:
  - Why populations change.
  - Why there are so many different kinds of organisms on Earth.
  - Why some organisms that look alike are only distantly related.
  - Why some organisms that look very different are actually closely related?
- Know that both Darwin and Wallace developed the theory of evolution by natural selection at the same time.

Check Your Understanding

- What does the word evolution refer to when used in day to day conversations?
- What does biological evolution mean?
- Who primarily proposed the theory of evolution by natural selection?

Introduction

Biological evolution is change in species over time. The idea of evolution was proposed by many people before Charles Darwin (**Figure** 10.110.1) began collecting evidence for the idea. Scientists for hundreds of years had hypothesized that species change over time.

1. Jean Baptiste **Lamarck** (1744–1829) was an important French naturalist. He was one of the first scientists to propose that species change over time. However, Lamarck was wrong about how species change. His idea of the **inheritance of acquired characteristics** is incorrect. Traits an organism develops during its own life time cannot be passed on to offspring, as Lamarck believed.
2. Charles **Lyell** (1797–1875) was a well-known English geologist. Darwin took Lyell's book, *Principles of Geology,* with him on the *Beagle*. In the book, Lyell argued that gradual geological processes have gradually shaped Earth's surface. From this, Lyell inferred that Earth must be far older than most people believed.
3. Thomas **Malthus** (1766–1834) was an English economist. He wrote an essay titled *On Population*. In the essay, Malthus argued that human populations grow faster than the resources they depend on. When populations become too large, famine and disease break out. In the end, this keeps populations in check by killing off the weakest members.

But it was not until Darwin published his research and detailed analysis that the idea of evolution started to gain widespread acceptance. Darwin's theory of evolution by natural selection brings all fields of biology together and

illuminates nearly every aspect of biology. As one famous biologist said, "Nothing in biology makes sense except in the light of evolution."

FIGURE 10.1
Charles Darwin was one of the most influential scientists who has ever lived. Darwin introduced the world to the theory of evolution by natural selection, which laid the foundation for how we understand the living world today.

Evolution by natural selection explains:

- The tremendous variety of organisms on Earth.
- Why some organisms that resemble each other are distantly related.
- Why some organisms that do not resemble each other are closely related.

There are three parts to Darwin's Theory of Evolution by Natural Selection.

1. Evolution, which is change in species over multiple generations (**Figure** 10.210.2).
2. Natural selection, in which individuals of a population that are most likely to survive and reproduce are also most likely to pass on traits that have a genetic basis to any offspring.
3. Adaptation, which are traits that a plant or animal is born with that helps them survive and reproduce in a particular environment. Adaptations are the result of natural selection. For example, light-colored moths on dark trees might be easier for birds to see and catch than dark moths on dark-colored trees. If the moths' color has a genetic basis, then after many generations of birds catching more light moths than dark moths, the population of moths will consist mostly of dark moths.

In everyday English, "evolution" simply means to "change" or a "stepwise change from simple to complex." In biology, **evolution** means change in the inherited traits of a group of organisms over multiple generations (**Figure** 10.3). Biological evolution has changed biologists' understanding of all life on Earth.

Darwin's Observations

Most people in the world did not become aware of the theory of evolution until 1859, when Charles Darwin published his book *On the Origin of Species by Means of Natural Selection*. This book described the observations and evidence that he collected over 20 years of intensive research, beginning with a five-year voyage around the world on a British research ship, the *HMS Beagle*. During this five-year voyage (**Figure** 10.4), Darwin was able to make observations about plants and animals spread around the world, and to collect specimens to study when he returned to England. Each time the Beagle stopped at a port to do some trading, Darwin went on land to explore and look for the local plants, animals, and fossils. One of the most important things Darwin did was to keep a diary. He took extremely detailed notes and drawings about everything he saw as well as his thoughts.

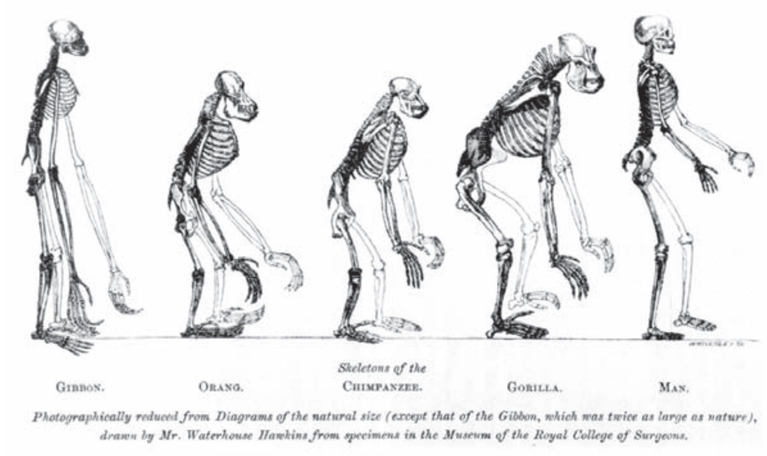

FIGURE 10.2
Humans and the other apes in this drawing all evolved from a common apelike ancestor.

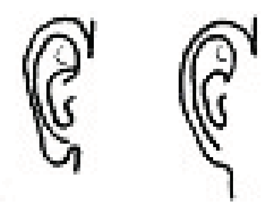

FIGURE 10.3
Human earlobes may be free or attached. You inherited the particular shape of your earlobes from your parents. Inherited traits are influenced by genes, which are passed on to offspring and future generations. Your summer tan is not passed on to your offspring. Natural selection only operates on traits like earlobe shape that have a genetic basis, not on traits like a summer tan that are acquired.

FIGURE 10.4
Charles Darwins famous five year voyage was aboard the from 1831-1836.

The Galápagos Islands

The around the world voyage of the *HMS Beagle* was mostly to map the coastline of South America. Darwin's best known discoveries were made on the Galápagos Islands (**Figure** 10.5), a group of 16 volcanic islands near the equator about 600 miles from the west coast of South America. Darwin was able to spend months on foot exploring the islands. Darwin's Theory of Evolution by Natural Selection was a result of his observations and over 20 years of examining the specimens he had collected and sent back to England, many of which came from these islands.

Darwin was amazed by the array of life he saw on the Galápagos Islands. He saw animals unlike anything he had

FIGURE 10.5
The Galpagos Islands are a group of 16 volcanic islands 972 km off the west coast of South America. The islands are famous for their many species found nowhere else.

ever seen before. Darwin was struck by how the same kind of animal differed from one island to another. For example, the iguanas (large lizards) differed between islands (**Figure** 10.6). The members of one iguana species spent much of their time swimming and diving underwater for seaweed, while those of another iguana species lived on land and ate cactus. In England, he was accustomed to watching cormorants fly, so he was surprised to find flightless cormorants on the islands alongside flying cormorants.

FIGURE 10.6
The Galpagos land iguanas are among the signature animals of the Galpagos Islands.

Giant Tortoises

Giant tortoises (**Figure** 10.7), large enough for two men to ride on, plodded across the islands and foraged on super tough leaves. Some of the tortoise species were found on only one island. Darwin was fascinated by the number of ways that organisms were well-suited to their environments. Even the tortoise shells were specially adapted to the conditions. Tortoises that ate plants near the ground had rounded shells, while the tortoises that stretched their necks to reach plants higher in shrubs had shells that bent upwards, allowing them to stretch their necks upward (**Figure** 10.810.8).

FIGURE 10.7
The name Galpagos means giant tortoise. When Darwin arrived on the Galpagos Islands, he was amazed by the size and variety of shapes of these animals. The giant tortoise is a unique animal found only in the Galpagos Islands. There are only about 200 tortoises remaining on these islands.

FIGURE 10.8
This tortoise is able to reach leaves high in shrubs with its long neck and curved shell.

Darwin's Finches

The most extensively studied animals on the Galápagos are the finch species (birds) (**Figure** 10.910.9). When Darwin first observed the finches on the islands, he did not even realize they were all finches. But when he studied them further, he realized they were all the same type of bird, and that each island had its own distinct species of finch. The birds on different islands had many similarities, but their beaks differed in size and shape.

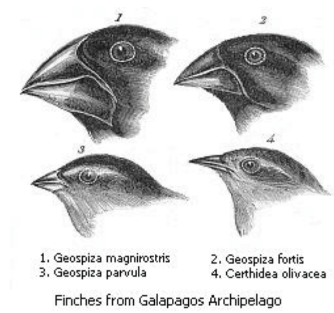

FIGURE 10.9
Four of Darwins finch species from the Galpagos Islands. The birds came from the same finch ancestor. They evolved as they adapted to different food resources on different islands. The first bird uses its large beak to crack open and eat large seeds. Bird #3 is able to pull small seeds out of small spaces.

In his diary, Darwin pointed out how each animal is well-suited for its particular environment. The shapes of the finch's beaks on each island were well-matched with the seeds available on their particular island, but not the seeds on other islands. A larger and stronger beak was needed to break open large seeds and a small beak was needed to feed on some of the smallest seeds.

Darwin also noticed how different species were distributed around the world. The finch, tortoise and other species

found on the Galápagos Islands were similar to species on South America, the nearest continent. Yet they also differed. Likewise, species he saw on islands *near* Africa were similar to, but different from species *on* Africa.

Return to England

When Darwin returned to England five years later, he did not rush to announce his discoveries. Unlike other naturalists before him, Darwin did not want to present any ideas unless he had strong evidence supporting them. Instead, once Darwin returned to England, he spent over twenty years examining specimens, talking with other scientists and collecting more information before he presented his theories. Darwin's observations eventually resulted in the Theory of Evolution by Natural Selection. His now famous book, *The Origin of Species* is a diary of his explorations and discussion on how he interpreted his observations (**Figure** 10.1010.10).

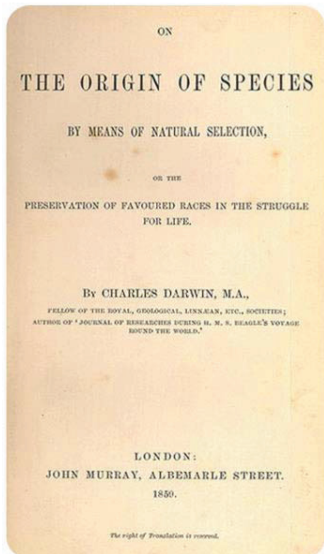

FIGURE 10.10
Charles Darwin presented the Theory of Evolution by Natural Selection in this book. The theories were based on evidence he collected and tested.

Other Influences on Darwin

How did Darwin come up with his theories? Some of Darwin's idea conflicted with widely held beliefs, included those from religious leaders, such as:

- All organisms never change and never go extinct, they are fixed.
- The world is only about 6,000 years old.

It was because of these widely held beliefs that Darwin delayed in presenting his findings.

Charles Darwin was influenced by the ideas of several people.

Before his voyage on the Beagle:

1. Jean-Baptiste Lamarck proposed the idea that evolution occurs. However, Darwin differed with Lamarck on several other points. Lamarck proposed that traits acquired during one's lifetime could be passed to the next generation.
2. Darwin's grandfather, Erasmus Darwin, wrote a book called *Zoonomia*. Charles Darwin was influenced by many of his grandfather's ideas including his descriptions of how species change (evolve) through artificial selection. During artificial selection, people choose specific traits to pass to the next generation, such as with horse or dog breeding (see below).
3. Charles Lyell, a well-known geologist and one of Darwin's instructors. Darwin learned about geology, paleontology and the changing Earth from Lyell. These findings suggested the Earth must be much older than 6,000 years.
4. Thomas Malthus: Darwin's ideas of natural selection were inspired by reading an essay by Thomas Malthus, an economist who suggested that humans could overpopulate and potentially exhaust food supplies. Darwin thought this must be especially true for animals, as they have a tendency to have more offspring than people have. There would therefore be a competition for survival.
5. Charles Darwin came upon some of his ideas about natural selection and adaptations from reading about artificial selection and breeding dogs. All dogs, from Chihuahuas to St. Bernards are part of the same genus as wolves (*Canis lupus*). Humans created the different breeds of dogs by selecting dogs with specific traits to breed together. For example, greyhounds were created by selecting the fastest runners and breeding them together (**Figure** 10.1110.11).
6. After the Voyage of the Beagle: Alfred Russel Wallace, another naturalist, also developed a theory of evolution by natural selection. Alfred Wallace toured South America and came up with a very similar theory of evolution by natural selection at the same time that Darwin did. Darwin and Wallace presented their theories and evidence in public together. Because of the vastness of Darwin's data, and his book, he is mostly credited and associated with this theory.

Natural Selection and Adaptation

The Theory of Evolution by Natural Selection means that the inherited traits of a population change over time through natural selection. Inherited traits are features that are passed from one generation to the next. For example, your eye color is an inherited trait (you inherited from your parents). Acquired traits are features such as strong muscles from working out.

Natural selection happens when some organisms have traits that make them better suited (they have better accommodation) to live in a certain environment than others. They are more likely to survive, reproduce and pass their traits on to future generations than those without the special traits. The process of natural selection helps us understand how organisms appear to be so well suited or adapted to their environments. Every plant and animal depends on its traits to survive. Survival may include getting food, building homes, and attracting mates. Most of these traits have been changed through natural selection so they allow a plant, animal, or bacteria to survive and reproduce relatively well in their environments. These traits are called adaptations. As environments have changed considerably over time, organisms must constantly adapt to those environments. It is the great diversity of species that increases the chance that at least some organisms adapt and survive any major changes in the environment.

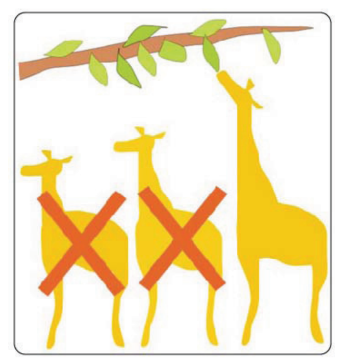

FIGURE 10.12
Natural selection involves (1) heritable variation (here, giraffe neck length); (2) overproduction of offspring (3 giraffes born, not all can survive); (3) differential survival and reproduction (not enough food for all giraffes; those with shorter necks starve); and (4) gradual change in traits in the population (long-necked giraffes survive and reproduce, so their genes for long necks increase in frequency in the next generation).

Imagine how in winter dark fur makes a rabbit easy for fox to spot and catch in the snow. Natural selection suggests that white-fur is an advantageous trait that improves the chance that a rabbit will survive, reproduce and pass the

FIGURE 10.11
Darwins grandfather had a big influence on Darwins ideas by introducing him to artificial selection of dogs and horses. Humans have created hundreds of dog breeds by selecting which dogs to breed based on certain features, such as size, coloration, speed, or facial features.

trait of white fur on to future generations (**Figure** 10.13). Dark fur rabbits will become uncommon.

FIGURE 10.13
In winter, the fur of Arctic Hares turns white. The camouflage may make it more difficult for fox and other predators to locate hares against the white snow.

Polygenic Inheritance and Natural Selection

But natural selection leading to evolution does not just select for certain individuals, it selects for groups. More than one individual must adapt to the environment to maintain a population. Natural selection determines which groups of organisms survive, based on their traits, and which do not, that is, natural selection determines the differential survival of groups of organisms.

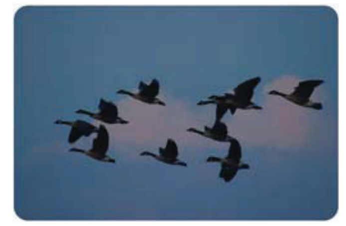

FIGURE 10.14
Natural selection determines the survival of groups of organisms. Flight as shown in these geese is an evolutionary step that probably aided in the survival of many birds.

Although some traits are determined by a single gene, many are influenced by more than one gene (polygenic). The result of polygenic inheritance is a continuous spectrum of phenotypic values which often show a bell curve pattern of distribution.

Given this pattern of phenotypic variability, natural selection can take three forms (**Figure** 10.15). We will use the hypothetical color distribution in this figure to illustrate the three types of selection. **Directional selection** shifts the frequency curve away from the average by favoring individuals with an extreme form of the variation. The curve would still be bell-shaped, but it would have shifted to the left or right, in the direction of the lighter or darker alleles. **Stabilizing selection** selects for a group of phenotypically average individuals, with individuals with either extreme phenotype selected against. **Disruptive selection** selects for groups of individuals with extreme phenotypes, selecting against individuals with the average phenotype.

Lesson Summary

- Evolution is change in species over multiple generations.
- Natural selection is how evolution occurs.
- Adaptations are the result of natural selection.
- Charles Darwin is credited with developing the Theory of Evolution by Natural Selection
- Darwin collected much of his evidence on a five year voyage around the world, with much of his data collected on the Galápagos Islands.
- The work of many others contributed to Darwin's theory.

Review Questions

1. What is biological evolution?
2. What is natural selection?
3. What is adaptation?
4. What is the difference between an inherited trait and an acquired trait?
5. What was the name of the ship that Darwin traveled on?
6. What is the name of the islands where Darwin studied evolution?
7. A giraffe's long neck allows the giraffe to eat leaves from high in the tree. This is an example of an ________-______.
8. Who proposed a theory of evolution by natural selection that was similar to Darwin's theory?

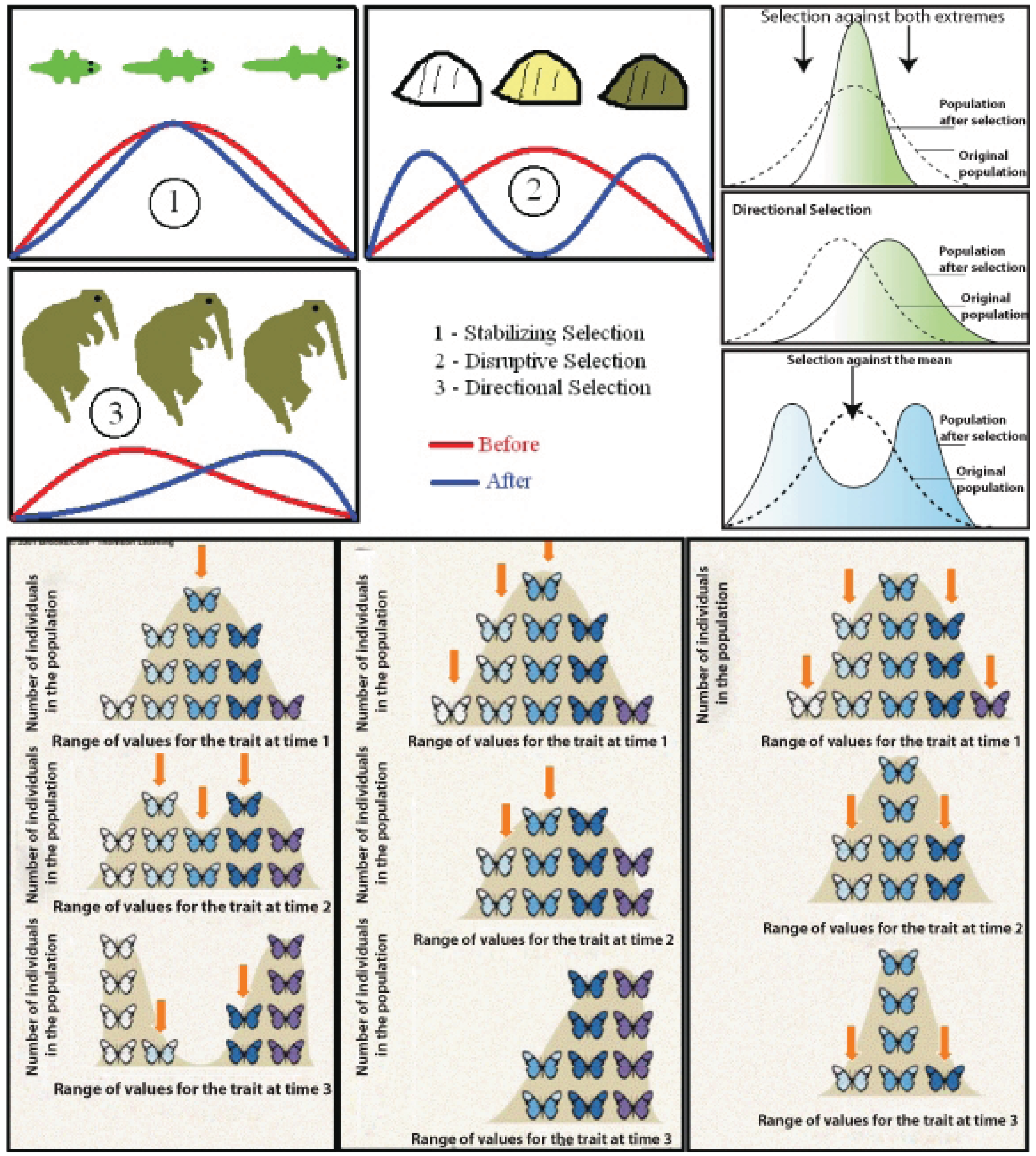

FIGURE 10.15

Three types of selection can alter allele frequencies, causing microevolution. The effect of stabilizing selection (1) is to select for the average phenotype, reducing variation. Disruptive selection (2) results in two different populations, which may eventually be isolated from one another. Directional selection (3) selects for a group of individuals with a single characteristic.

Points to Consider

- Evolution by natural selection is supported by extensive scientific evidence. What do you think this evidence consists of?

10.2 Evidence of Evolution

Lesson Objectives

- Understand that the scientific theory of biological evolution is based on extensive physical evidence and testing. This includes:
  - differences between fossils in different layers of rock
  - the age of rocks and fossils
  - vestigial structures
  - similarities between embryos of different organisms
  - the same DNA and RNA materials found in all organisms
  - similar genomes found in almost all organisms.

Check Your Understanding

- Where did Charles Darwin collect evidence of evolution and what kinds of evidence did he find?
- What is natural selection?
- What kinds of traits change through evolution?

Introduction

Though the idea of evolution had been proposed prior to Charles Darwin, most people think of Darwin's name when they think of evolution. Unlike others before him who based their ideas on speculation, opinions, myths, or folklore, Darwin's theories were based on a tremendous amount of scientific evidence.

In 1859, Charles Darwin and Alfred Russel Wallace first presented several forms of evidence of evolution. Their evidence included:

- fossils of extinct species from different eras
- similarities between the embryos of different species
- physical traits of different species
- the behavior of different species
- the distributions of different plant and animal species around the world.

Darwin and other 19^{th} century scientists came to the conclusions they did without knowing anything about molecular biology. Today, even more evidence of evolution by natural selection is coming from molecular biology and genetics. Genetics is also helping explain the mechanisms of how evolution occurs.

The Fossil Record

Paleontologists are the scientists who study fossils to learn about life in the past. **Fossils** are the preserved remains or traces of animals, plants, and other organisms from the distant past. Examples of fossils include bones, teeth, impressions, and leaves. Paleontologists compare the features of species from different periods in history. With this information, they try to unravel how species have evolved over millions of years (**Figure** 10.1610.16). This method works better with some species than others. For example, it is difficult to track the evolution of bacteria from fossils, because their single cells do not last well as fossils.

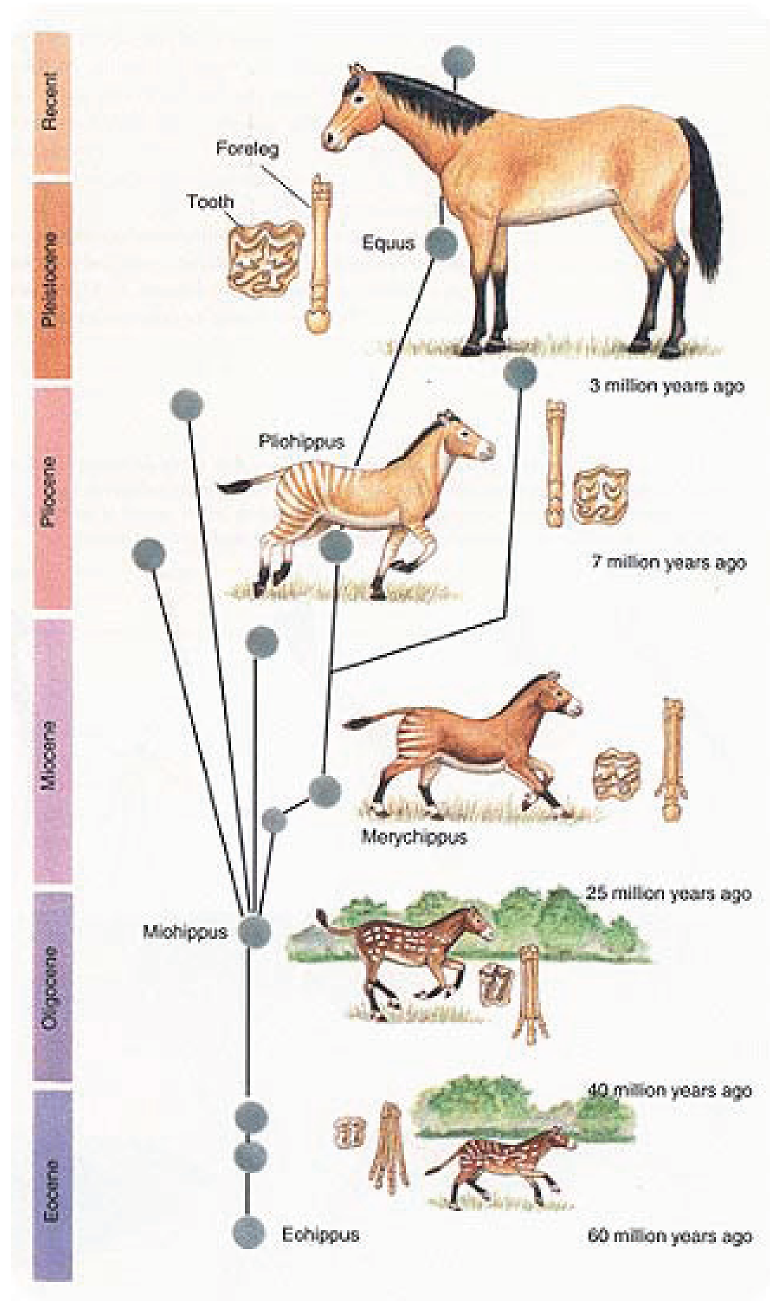

FIGURE 10.16
Evolution of the horse. Fossil evidence, depicted by the skeletal fragments, demonstrates evolutionary milestones in this process. Notice the 57 million year evolution of the horse leg bones and teeth. Especially obvious is the transformation of the leg bones from having four distinct digits to the conformation of today's horse.

Until recently, fossils were the main source of evidence of evolution (**Figures** 10.17 and 10.18). The location of each fossil in layers of rocks provides clues to the age of the species and how species evolved in the past. Older materials and fossils are deeper in the earth; newer fossils and materials are closer to the surface.

FIGURE 10.17
A fossil is the remains of a plant or animal that existed some time in the distant past. Fossils, such as this one, were found in rocks or soil that was laid down long ago.

FIGURE 10.18
About 40 to 60 million years ago this mosquito and fly were trapped in the gooey stuff, called resin that comes from trees. The fossils in the movie , were trapped in resin.

Fossils and the rocks they are embedded in provide evidence of how life and environmental conditions have changed throughout Earth's history. They also help us understand how the past and present distribution of life on Earth is affected by earthquakes, volcanoes, and shifting seas, and other movements of the continents.

The Age of Rock Layers and Fossils

The many layers of sedimentary rock provide evidence of the long history of Eearth and the order of life forms whose remains are found in the rocks. The youngest layers are not always found on top, because of folding, breaking, and uplifting of layers. If the layers of earth were tilted by earthquakes or volcanoes, geologists can determine which layers came from the deepest parts of the Earth.

The fossils and the order in which fossils appear is called the fossil record. This record provides important records of how species have evolved, divided and gone extinct. Methods used to date the age of rocks and fossils make it possible to determine when these events occurred.

Geologists use a method called radiometric dating to determine the age of rocks and fossils in each layer of rock. This technique measures the decay rate of radioactive materials in each rock layer (**Figure** 10.19).

FIGURE 10.19
This device, called a spectrophotometer can be used to measure the level of radioactive decay of certain elements in rocks and fossils to determine their age.

Radiometric dating has been used to determine that the oldest known rocks on Earth are between 4 and 5 billion years old. The oldest fossils are between 3 and 4 billion years old.

Evolutionary Structures

Millions of species of animals, plants and microorganisms are alive today. Even though two different species may not look similar, they may have similar internal structures, and chemical processes that indicate they can have a common ancestor.

Some of the most interesting kinds of evidence for evolution are body parts that have lost their use through evolution (**Figure** 10.20). Most birds need their wings to fly. But the wings on an ostrich have lost their original use. These are called **vestigial structures**. Penguins do not use their wings to fly in the air; however they do use them to "fly" in the water. A whale's pelvic bones-which were once attached to legs- are also vestigial structures.

FIGURE 10.20

Mole rats live under ground where they do not need eyes to find their way around. This moles eyes are covered by skin. Body parts that do not serve any function are vestigial structures.

Homologous structures are structures that are similar in related organisms because they were inherited from a common ancestor. These structures may or may not have the same function in the descendants. **Figure** below shows the hands of several different mammals. They all have the same basic pattern of bones. They inherited this pattern from a common ancestor. However, their forelimbs now have different functions.

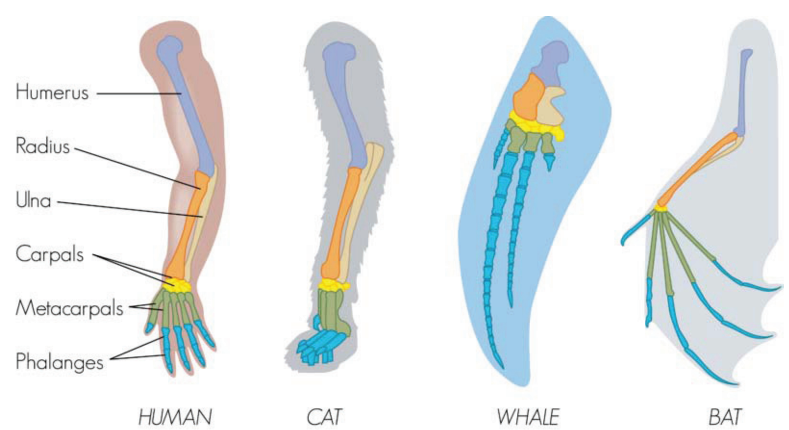

FIGURE 10.21

If you look at an x-ray of the bones in your back (called vertebrae), you will see several vertebrae that come under your hips. These are called your coccyx, or tailbone. We do not use these small vertebrae; they are further evidence of our evolution.

Analogous structures are structures similar in different organisms because they evolved in a *similar environment*,

rather than were inherited from a recent common ancestor. They usually serve the same or similar purposes. An example is the streamlined torpedo body shape of porpoises and sharks. So even though they evolved from different ancestors, porpoises and sharks developed analogous structures as a result of their evolution in the same aquatic environment.

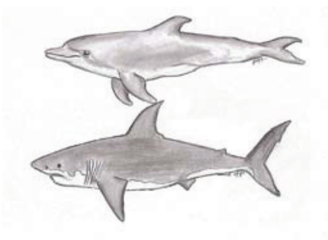

FIGURE 10.22
This picture shows two species, the Common Bottlenose Dolphin (Tursiops truncatus) and the Great White Shark (Carcharodon carcharias). These two species show several analogous structures, such as dorsal fins and streamlined body shape, that give them similar advantages in their environment despite their lack of common ancestry.

Embryological Evidence

Some of the oldest evidence of evolution comes from embryology, the study of how organisms develop. An embryo is an animal or plant in its earliest stages of development, before it is born or hatched.

Centuries ago, people recognized that the embryos of many different species have similar appearances (**Figure** 10.2310.23). The embryos of some species are even difficult to tell apart. Many of these animals do not differ much in appearance until they develop further. Many traits of one type of animal appear in the embryo of another type of animal. For example, fish embryos and human embryos both have gill slits. In fish they develop into gills, but in humans they disappear before birth (**Figure** 10.2410.24).

The similarities between embryos suggests that these animals are related and have common ancestors. For example, humans did not evolve from chimpanzees. But the similarities between the embryos of both species may be due to our development from an ancestor we have in common with chimpanzees. As our common ancestor evolved, humans and chimpanzees diverged and developed different traits.

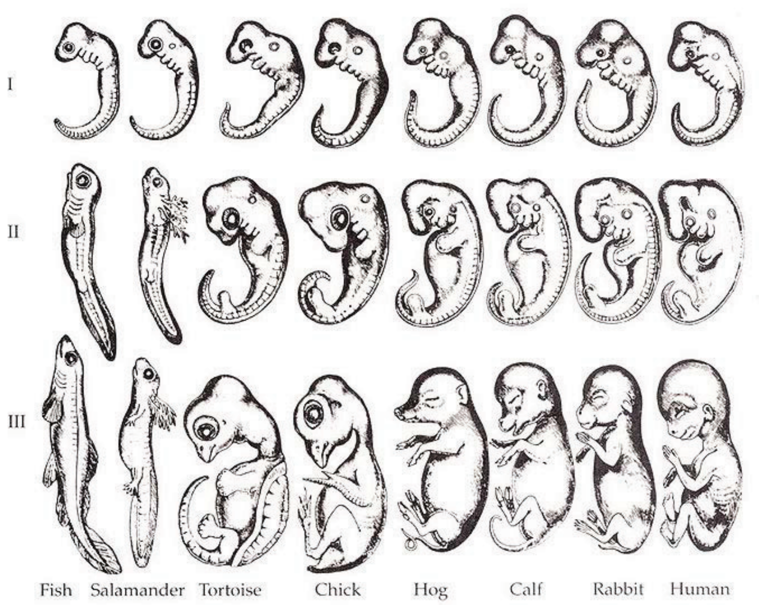

FIGURE 10.23
This drawing was made to show the similarities between the embryos of many species. Embryos of many different kinds of animals: mammals, birds, reptiles, fish, etc. look very similar.

FIGURE 10.24
This is a six week old human embryo. Notice the similarities between this embryo and those of the other animals in figure 3.

Similarities Between Molecules and Genomes

Molecular Clocks

Arguably, some of the most significant evidence of evolution comes from examining the molecules and DNA found in all organisms (**Figure** 10.2510.25). The field of molecular biology did not emerge until the 1940s and has since confirmed and extended the conclusions about evolution drawn from other forms of evidence. **Molecular clocks** are used in molecular evolution to relate the time that two species diverged to the number of differences measured between the species' DNA sequences or protein amino acid sequences. These clocks are sometimes called gene clocks or evolutionary clocks. The fewer the differences the less time since the divergence of the species. For example, a chicken and a gorilla will have more differences between their DNA and protein amino acid sequences then a gorilla and an orangutan. This provides additional evidence that the gorilla and orangutan are evolutionally closer related than the gorilla and the chicken.

Molecular clocks, combined with other forms of evidence, such as evidence from the fossil record, have provided considerable evidence to estimate how long ago various groups of organisms diverged evolutionarily from one another.

Molecular Genetics

The development of molecular genetics has revealed the record of evolution left in the genomes of all organisms (**Figure** 10.26). It also provides new information about the relationships among species and how evolution occurs.

Molecular genetics provides evidence of evolution such as:

- the same biochemical building blocks – such as amino acids and nucleotides - are responsible for life in all organisms, from bacteria to plants and animals
- DNA and RNA determine the development of all organisms
- the similarities and differences between the genomes, the gene sequences of each species, reveal patterns of evolution.

Lesson Summary

- Fossil evidence, depicted by the skeletal fragments, demonstrates evolutionary milestones.
- Fossils and the rocks they are embedded in provide evidence of how life and environmental conditions have changed throughout Earth's history.
- The fossils and the order in which fossils appear is called the fossil record.

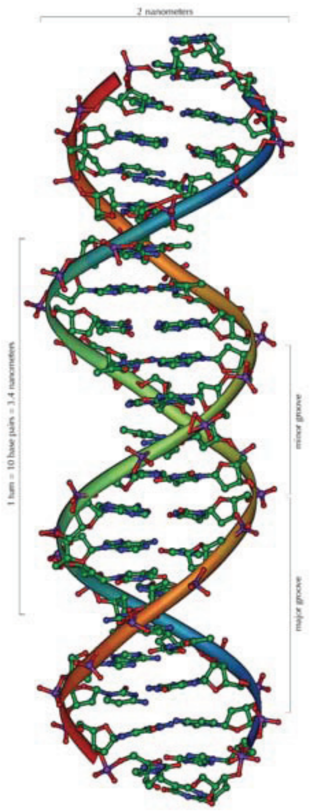

FIGURE 10.25
Almost all organisms are made from DNA with the same building blocks. The genomes (all of the genes in an organism) of all mammals are almost identical.

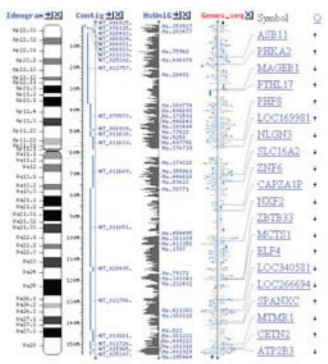

FIGURE 10.26
This is a map of the genes on just one of the 46 human chromosomes. Similarities and differences between the genomes (the genetic makeup) of different organisms reveal the relationships between the species. The human and chimpanzee genomes are almost identical- just about 1.2% differences between the two genomes. The complexity of the map signifies close evolutionary relationships when the genomes are highly similar.

- Geologists use a method called radiometric dating to determine the age of rocks and fossils in each layer of rock.
- Radiometric dating has been used to determine that the oldest known rocks on Earth are between 4-5 billion years old. The oldest fossils are between 3-4 billion years old.
- Body parts that do not serve any function are called vestigial structures.
- Vestigial structures indicate that two species have a recent common ancestor.
- The similarities between embryos suggests that animals are related and have common ancestors.
- The same biochemical building blocks – such as amino acids and nucleotides - are responsible for life in all organisms, from bacteria to plants and animals.
- DNA and RNA determines the development of all organisms.
- The similarities and differences between the genomes, the gene sequences of each species, reveal patterns of

evolution.

Review Questions

1. What are the different kinds of evidence of evolution?
2. How do geologists determine the age of rocks and fossils?
3. What is an embryo?
4. What is a vestigial structure?
5. What is an example of a vestigial structure?
6. What is a genome?
7. What is the most convincing evidence of evolution?
8. How do the embryos of different species support the idea of evolution?

Points to Consider

- How do you think new species evolve?
- How long do you think it takes for a new species to evolve?

10.3 Macro and Micro Evolution

Lesson Objectives

- Students will understand the differences between macroevolution and microevolution.
- Students will understand that speciation is the formation of new species.
- Students will understand the mechanisms of speciation.

Check Your Understanding

- Why can't an individual person evolve? Why can only groups evolve over many generations?
- What causes a species or a population to evolve?

Introduction

Small changes or large changes, how does evolution occur? It is easy to think that many small changes, as they accumulate over time, may gradually lead to a new species. Or is it possible that due to severe changes in the environment, large changes are needed to allow species to adapt to the new surroundings? Or are both probable methods of evolution?

Microevolution and Macroevolution

You already know that evolution is the change in species over time, due to the change of how often an inherited trait occurs in a population over many generations. Most evolutionary changes are small and do not lead to the creation of a new species. These small changes are called microevolution.

An example of microevolution is the evolution of pesticide resistance in mosquitoes. Imagine that you have a pesticide that kills most of the mosquitoes in your state one year. As a result, the only remaining mosquitoes are the pesticide resistant mosquitoes. When these mosquitoes reproduce the next year, they produce more mosquitoes with the pesticide resistant trait. This is an example of microevolution because the number of mosquitoes with this trait changed. However, this evolutionary change did not create a new species of mosquito, because the pesticide resistant mosquitoes can still reproduce with other mosquitoes if they were put together.

Macroevolution refers to much bigger evolutionary changes that result in new species. Macroevolution may happen:

1. when many microevolution steps lead to the creation of a new species,
2. as a result of a major environmental change, such as volcanic eruptions, earthquakes or an asteroid hitting Earth, which changes the environment so much that natural selection leads to large changes in the traits of a species.

After thousands of years of isolation from each other, some of Darwin's finch population will not or cannot breed with other finch populations when they are brought together. Since they do not breed together, they are classified as separate species.

Genotype or Phenotype?

Natural selection acts on the **phenotype**, physical characteristics, of an individual. For many traits, the homozygous **genotype**, combination of alleles, *AA* for example, has the same phenotype as the heterozygous *Aa* genotype. If both an *AA* and *Aa* individual have the same phenotype, the environment cannot distinguish between them. So natural selection cannot choose a homozygous individual over a heterozygous individual. If homozygous recessive *aa* individuals are selected against, that is they are not well adapted to their environment, acting on the phenotype allows the *a* allele to be maintained in the population through heterozygous *Aa* individuals.

Carriers

Because natural selection acts on the phenotype, if an allele is lethal in a homozygous individual, *aa* for example, it will not be lethal in a heterozygous *Aa* individual. These heterozygous *Aa* individuals will then act as carriers of the *a* allele. This allele is then maintained in the population's gene pool. The gene pool is the complete set of alleles within a population.

Tay-Sachs disease is an autosomal recessive genetic disorder. It is caused by a genetic defect in a single gene with one defective copy of that gene inherited from each parent, *rr* for example. Affected individuals usually die from complications of the disease in early childhood. Affected individuals must have unaffected parents, each being a carrier of the defective allele, so the parents are heterozygous *Rr*. This lethal allele is maintained in the gene pool through these unsuspecting heterozygous individuals; they do not show any symptoms of the disease, so most individuals do not get tested to see if they are carriers.

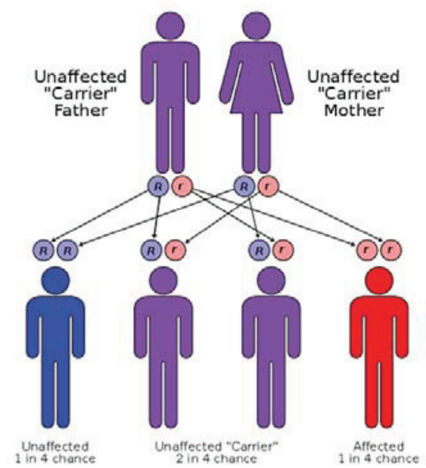

FIGURE 10.27
Tay-Sachs disease is inherited in the autosomal recessive pattern. Each parent is an unaffected carrier of the lethal allele.

Genetic Drift

Variations in allele frequencies that occur by chance are minimal in large populations. In small populations, random variations in allele frequencies can significantly influence the "survival" of any allele. Random changes in allele frequencies in small populations is known as genetic drift. As the population (and therefore the gene pool) is small, genetic drift could have substantial effects on the traits and diversity of a population. Many biologists think that genetic drift is a major cause of microevolution.

1. **Bottleneck effect** occurs when a population suddenly gets much smaller. This might happen because of a natural disaster such as a forest fire. By chance, allele frequencies of the survivors may be different from those of the original population.
2. **Founder effect** occurs when a few individuals start, or found, a new population. By chance, allele frequencies of the founders may be different from allele frequencies of the population they left. An example is described in the **Figure** 10.28.

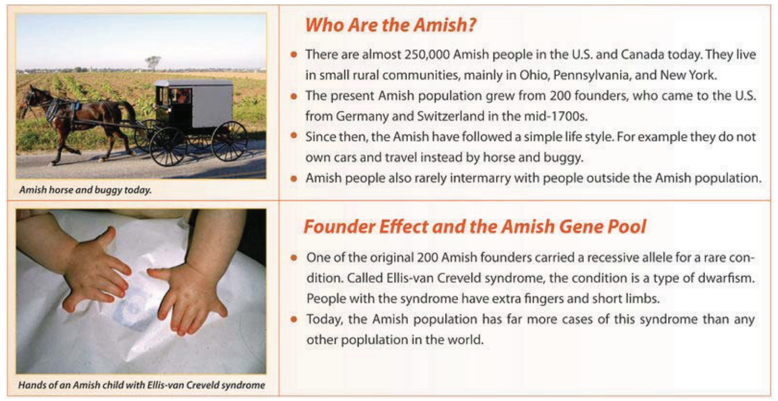

FIGURE 10.28

The Origin of Species

The creation of a new species is called **speciation**. Most new species develop naturally, but humans have also artificially created new subspecies, breeds, and species for thousands of years.

Natural selection causes beneficial heritable traits to become more common in a population, and unfavorable heritable traits become less common. For example, a giraffe's neck is beneficial because it allows the giraffe to reach leaves high in trees. Natural selection caused this beneficial trait to become more common than short necks.

As new mutations (changes in the DNA sequence) are constantly being generated in a population's gene pool, some of these mutations will be beneficial and result in traits that allow adaptation and survival. Natural selection causes evolution through the genetic change of a species as the beneficial traits become more common within a population.

Artificial selection is when humans select which plants or animals to breed to pass specific traits on to the next generation. A farmer may choose to breed only the cows that produce the best milk (the favored traits) and not breed cows that do not produce much milk (a less desirable trait). Humans have also artificially bred dogs to create new breeds (**Figure** 10.29).

FIGURE 10.29
Artificial Selection: Humans used artificial selection to create these different breeds. Both dog breeds are descended from the same wolves, and their genes are almost identical. Yet there is at least one difference between their genes that determine size.

Reproductive Isolation

There are two main ways that speciation happens naturally. Both processes create new species by isolating groups (populations) of the same species from each other. Organisms can be reproductively isolated from each other either geographically or by some behavior. Over a long period of time (usually thousands of years), each population evolves in a different direction. One way scientists test whether two populations are separate species is to bring them together again. If the two populations do not interbreed and produce fertile offspring, they are separate species.

Geographic Isolation

Allopatric speciation happens when groups from the same species are geographically isolated physically for long periods. Imagine all the ways that plants or animals could be isolated from each other:

- a mountain range
- a canyon
- water such as rivers, streams, or an ocean
- a desert

Charles Darwin recognized that speciation could happen when some members of a species were isolated from the others for hundreds or thousands of years. Darwin had observed thirteen distinct finch species on the Galápagos Islands that had evolved from the same ancestor. Several of the finch populations evolved into separate species while they were isolated on separate islands. Scientists were able to determine which finches had evolved into distinct species by bringing members of each population together. The birds that would not or could not interbreed were regarded as separate species.

A classic example of geographic isolation is the Abert squirrel, shown in **Figures** 10.30) and 10.31). When the Grand Canyon in Arizona formed, squirrels from one species were separated by the giant canyon that they could not cross. After thousands of years of isolation from each other, the squirrel populations on the northern wall of the canyon looked and behaved differently from those on the southern wall. North rim squirrels have white tails and black bellies. Squirrels on the south rim have white bellies and dark tails.

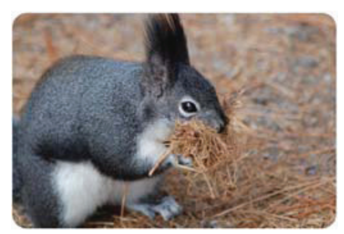

FIGURE 10.30
Abert Squirrel on the southern rim of the Grand Canyon

FIGURE 10.31
Kaibab squirrel (a subspecies of Aberts) found on northern rim of the Grand Canyon

Isolation without Physical Separation

Sympatric speciation happens when groups from the same species stop interbreeding, because of something other than physical separation, such as behavior. The separation may be due to different mating seasons, for example. Sympatric speciation is more difficult to identify.

Some scientists suspect that two groups of orcas (killer whales) live in the same part of the Pacific Ocean part of the year, but do not interbreed. The two groups hunt different prey species, eat different foods, sing different songs, and have different social structures.

Different behaviors may have also led to the emergence of two Galápagos finch species that live in the same space. The two species are separated by behavioral barriers such as mating signals. In this case, members of each group select mates according to different beak structures and bird calls. They do not need physical barriers, because behavioral differences do enough to keep the groups separated.

Allopatric speciation and sympatric speciation are both forms of **reproductive isolation**. Allopatric speciation is due to **geographic isolation**. Sympatric speciation is due to **behavioral isolation**, or isolation due to different mating seasons, which is also known as **temporal isolation**.

Evolutionary Trees

Charles Darwin came up with the idea of an evolutionary tree to represent the relationships between different species and their common ancestors (**Figure** 10.3210.32). The base of the tree represents the ancient ancestors of all life. The separation into large branches shows where these original species evolved into increasingly different populations that would not come back together again. The branches keep splitting into smaller and smaller branches as species continue to evolve into more and more species. Some species are represented by short twigs spurting out of the tree, then stopping. These are species that went extinct before evolving into new species. Other "Trees of Life" have been created by other scientists (**Figure** 10.33).

Theory?

Darwin's Theory of Evolution by Natural Selection is supported by well over 150 years of scientific evidence, ranging from fossil evidence to DNA evidence. By definition, this is a well tested scientific theory. An abundance of scientific evidence supports this theory. The world is very old and has undergone some dramatic changes. Life has been on the planet for most of that time. As you will see in the next lesson, life started as single celled organisms and has evolved over billions of years into complex plants and animals. But this journey has not been easy. Most species

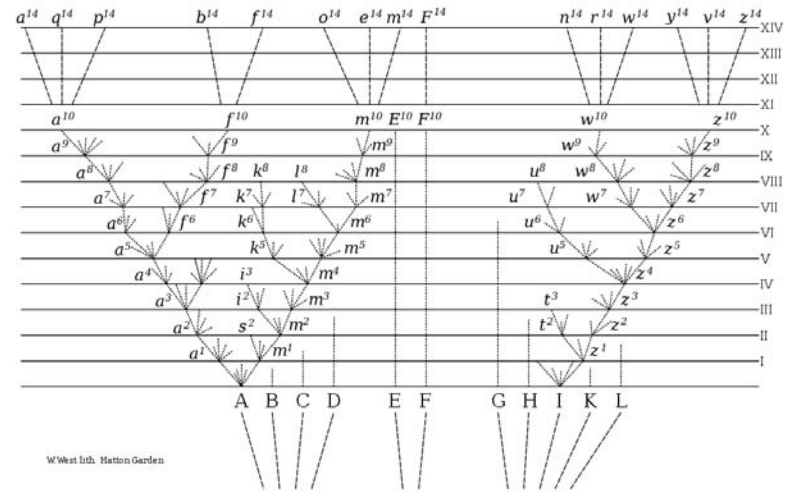

FIGURE 10.32
Darwin drew this version of the Tree of Life to represent how species evolve and diverge into separate directions. Each point on the tree where one branch splits off from another represents the common ancestor of the species on the separate branches.

that have ever lived are now extinct. There have been a number of mass extinctions, where many species vanished all at once. The tremendous diversity of species has allowed some to adapt to whatever changes nature throws in its path, from small changes to major environmental disturbances. So it is nature that selects - hence *Natural Selection* - which species adapts, survives and evolves.

Lesson Summary

- Microevolution results from evolutionary changes that are small and do not lead to the creation of a new species.
- Macroevolution refers to large evolutionary changes that result in new species.
- Macroevolution may happen when many microevolution steps lead to the creation of a new species.
- Macroevolution may happen as a result of a major environmental change, such as volcanic eruptions, earthquakes or an asteroid hitting Earth, which changes the environment so much that natural selection leads to large changes in the traits of a species
- The creation of a new species is called speciation.
- Natural selection causes beneficial heritable traits to become more common in a population, and unfavorable heritable traits become less common.
- Artificial selection is when humans select which plants or animals to breed to pass specific traits on to the next generation.
- Allopatric speciation occurs when groups from the same species are geographically isolated physically for long periods.
- Sympatric speciation occurs when groups from the same species stop interbreeding, because of something other than physical separation, such as behavior.
- Allopatric speciation and sympatric speciation are both forms of reproductive isolation.
- Not all organisms evolve at the same rate.
- Evolutionary trees are used to represent the relationships between different species and their common ancestors.

Review Questions

1. What is the difference between macroevolution and microevolution?
2. What conditions cause organisms to evolve and adapt?

3. Which organism has a faster rate of evolution: a human or a bacterium?
4. How do you know if two related organisms are members of the same species?
5. Why do the squirrels on opposite side of the Grand Canyon look different?
6. How is artificial selection different from natural selection?
7. What, other than physical isolation, could cause a species to split into two different directions of evolution?

Points to Consider

- How long do you think humans have been around?
- How long do you think Earth existed before life formed?
- For how much of Earth's history have humans existed?

10.4 History of Life on Earth

Lesson Objectives

- Know that geologists and paleontologists use evidence to determine the history of Earth and life on Earth.
- Know that geologists and paleontologists measure the radioactivity in certain rocks to determine the age of the earth and fossils.
- Know that the earth is between four and five billion years old.
- Know that scientists need to know what the environment (what chemicals were around, the temperature, etc.) was like on Earth billions of years ago to know how life formed.

Check Your Understanding

- What are fossils?
- How does the fossil record contribute to the evidence of evolution?

Introduction

It is no surprise that people have wondered about the age of the earth, how it was formed, and how life began on Earth for hundreds, even thousands, of years. Try to imagine how ancient philosophers tried to explain the history of the earth and life. Many people used mythology or cultural beliefs to explain elaborate stories about how and when the earth formed.

The past two to three hundred years has been an exciting time for geologists, paleontologists and other scientists who are trying to trace the history of the earth. What was once a hobby, studying land forms and fossils has become a science that is revealing the history of the earth and life on Earth.

Age of Earth

During the 1800s, geologists, paleontologists and naturalists found several forms of physical evidence that confirmed that the earth is very old, far older than the 6,000 years that some leaders had claimed. Their evidence included:

- Fossils of ancient sea life on dry land far from oceans: This supported the idea that the earth changed over time and that some dry land today was once covered by oceans.
- The many layers of rock: When people realized that rock layers represent the order in which rocks and fossils appeared, they were able to start to trace the history of the earth and life on Earth.
- Indications that volcanic eruptions, earthquakes and erosion that happened long ago shaped much of the earth's surface. This supported the idea of an older Earth.

Radiometric Dating

During the past one hundred years, geologists and paleontologists have been able to delve even deeper into the earth's history with new tools of science. The most convincing method, called **radiometric dating**, was developed more than one hundred years ago. Rocks are made up of minerals. Scientists found that they could measure the age of rocks by measuring the radioactivity of certain minerals in rocks. Geologists and paleontologists still use

variations of radiometric dating to determine the age of fossils and rocks today (**Figure** 10.33).

FIGURE 10.33
The most reliable way to figure out the earths age is to measure the radioactivity of certain minerals found in rocks (called radiometric dating). This mass spectrophotometer can also be used to measure age of fossils from the level of radiation in minerals surrounding the fossil.

Over 4 Billion Years

The earth is at least as old as its oldest rocks. The oldest rock minerals found on Earth so far are zircon crystals that are at least 4.404 billion years old. These tiny crystals were found in the Jack Hills of Western Australia. Since the earth is at least as old as the oldest minerals found on Earth, geologists estimate that the minimum age of the earth is 4.404 billion years.

Likewise, the earth cannot be any older than the solar system. The oldest possible age of the earth is 4.57 billion years old, the age of the solar system. Geologists and geophysicists based the age of the universe on the age of materials within meteorites that are formed within the solar system.

Origin of Life on Earth

There is good evidence that life has probably existed on Earth for most of Earth's history. Some of the oldest fossils of life forms on Earth are at least 3.5 billion year old fossils of blue green algae found in Australia (**Figure** 10.34).

FIGURE 10.34
Some of the oldest fossils on earth are stromolites, made of algae and a kind of bacteria, found along the coast of Australia.

The next step is to determine exactly how life formed billions of years ago. First, scientists need to know what the environment was like 3.5 to 4 billion years ago; they need to know what kinds of materials were available then that could have been involved in the creation of life. Scientists believe the early earth contained no oxygen gas, but did contain other gases, including nitrogen, carbon dioxide, carbon monoxide, water vapor, hydrogen sulfide and probably a few others.

Life from Random Reactions

Today, we have evidence that life on Earth came from random reactions between chemical compounds that formed molecules; in a series of random steps, these molecules created proteins and nucleic acids (RNA or DNA), and then cells. We know that the ingredients for life (the building blocks of life), were present at the beginning of Earth's history. Some chemicals were in water and volcanic gases. Other chemicals would have come from meteorites in space. Energy to drive chemical reactions was provided by volcanic eruptions and lightening. Keep in mind that this

process may have taken as much as 1 billion years. Our understanding of how life originated on Earth is developing gradually (**Figure** 10.35).

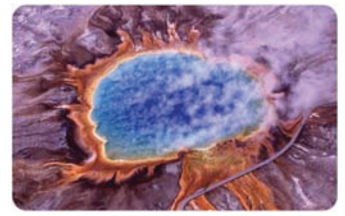

FIGURE 10.35
Some clues to the origins of life on Earth come from studying the early life forms that developed in hot springs, such as the Grand Prismatic Spring at Yellowstone National Park. This spring is approximately 250 feet by 300 feet wide.

Geologic Time Scale

Geologists and other earth scientists use geologic time scales to describe when events occurred throughout the history of Earth. The time scales can be used to illustrate when both geologic events and events affecting plant and animal life occurred. All of the earth events we see happening today, such as earthquakes, volcanic eruptions, and erosion, have happened throughout history. Past catastrophic events, such as asteroids and comets also hit the earth long before humans evolved.

The geologic time scale illustrates the timing of events such as:

- earthquakes
- volcanic eruptions
- major erosion
- meteorites hitting Earth
- the first signs of life forms
- mass exterminations

The geologic time scale is based on relative ages. No actual ages were placed on the original time scale.

Mass Extinctions

Extinctions are part of natural selection. Species often go extinct when their environment changes and they do not have the traits they need to survive. Only those individuals with the traits needed to live in a changed environment survive (**Figure** 10.36).

FIGURE 10.37
Humans have caused many extinctions by introducing species to new places. For example, many of New Zealands birds have adapted to nesting on the ground. This was possible because there were no land mammals in New Zealand until Europeans arrived and brought cats, fox and other predators with them. Several of New Zealands ground nesting birds, such as this flightless kiwi, are now extinct or threatened because of these predators.

Mass extinctions, such as the extinction of dinosaurs and many marine mammals, happened after major catastrophes such as volcanic eruptions and major earthquakes changed the environment. Scientists have been looking for

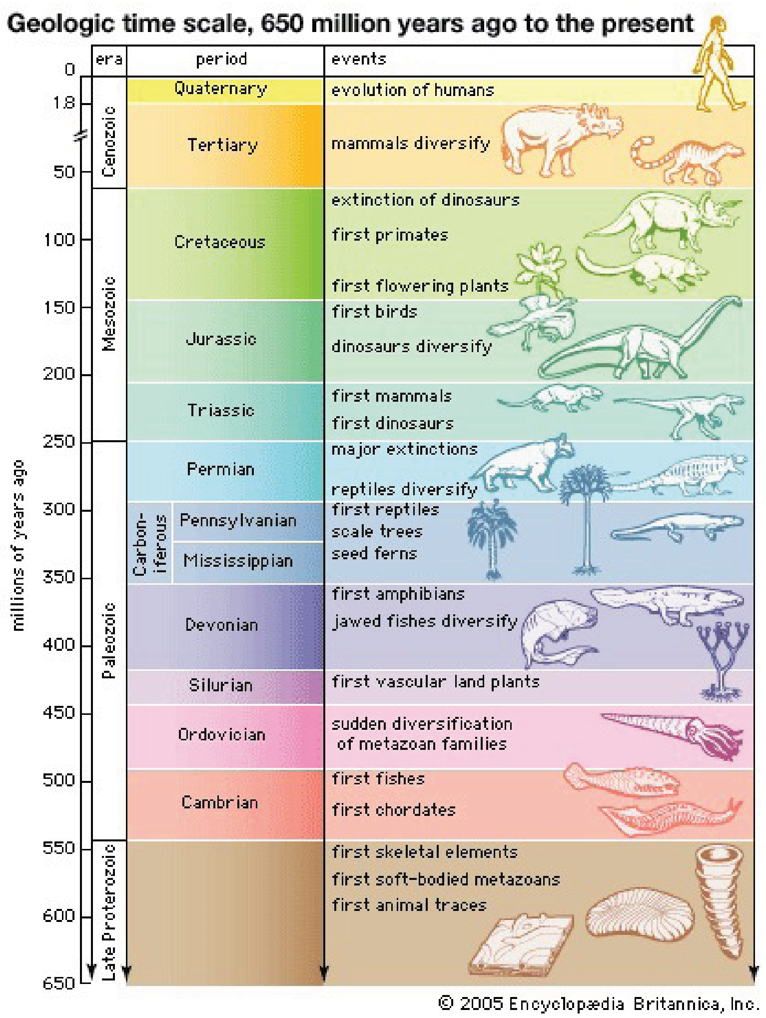

FIGURE 10.36

The Geologic time scale explains how the earth and life on it has changed over time.

evidence of why dinosaurs went extinct over fairly short periods. Many scientists are examining the theory that a major cataclysmic events, such as an asteroid colliding with Earth, may have caused the extinction of dinosaurs 65 million years ago (**Figure** 10.37).

FIGURE 10.38

The fossil of Tarbosaurus, one of the land dinosaurs that went extinct during one of the mass extinctions.

Since life began on Earth, there have been several major mass extinctions. If you look closely at the geological time scale, you will find that at least five major massive extinctions have occurred in the past 540 million years. In each mass extinction, over 50% of animal species died. The total number of extinctions could be as high as 20 mass extinctions during this period.

The fossil record tells the story of these mass extinctions: millions of species of fish, amphibians, reptiles, birds,

mammals, mosses, ferns, conifers, flowering plants, and fungi populated the seas and covered the Earth - as continents crashed together and broke apart, glaciers advanced and retreated, and meteors struck, causing massive extinctions. Two specific extinctions occurred at the end of the Permian period and when the dinosaurs went extinct.

At the end of the **Permian**, an estimated 99.5% of individual organisms perished. Several factors may have contributed, and one factor relates again to the supercontinent Pangaea. Marine biodiversity is greatest in shallow coastal areas. A single continent has a much smaller shoreline than multiple continents of the same size. Perhaps this smaller shoreline contributed to the dramatic loss of species, for up to 95% of marine species perished, compared to "only" 70% of land species. Although the exact cause remains unknown, fossils clearly document the fact of Earth's most devastating extinction.

FIGURE 10.39

The supercontinent Pangaea encompassed all of todays continents in a single land mass. This configuration limited shallow coastal areas which harbor marine species, and may have contributed to the dramatic event which ended the Permian - the most massive extinction ever recorded.

The dramatic extinction of all dinosaurs (except those which led to birds) marked the end of the **Cretaceous** period. A worldwide iridium-rich layer, dated at 65.5 million years ago, provides evidence for a dramatic cause for their ultimate extinction. Iridium is rare in the Earth's crust, but common in comets and asteroids. Scientists associate this layer with a huge crater in the Yucatan and Gulf of Mexico. A collision/explosion between the Earth and a comet or asteroid could have spread debris which set off tsunamis, altered the climate (including acid rain), and reduced sunlight 10-20%. A consequent reduction in photosynthesis would have caused a drastic decrease in food chains, leading to the extinction of the dinosaurs. The fossil record obviously depicts the presence of dinosaurs on Earth, and the absence of dinosaur fossils after this extinction event demonstrates the relationship between the fossil record and evolution.

FIGURE 10.40

The fossil record demonstrates the presence of dinosaurs, which went extinct over 65 million years ago.

After each mass extinction, open ecological niches are quickly filled by other species. This is well documented in

the fossil record. This episodic speciation following an event such as a mass extinction also shows the relationship between evolution and the fossil record.

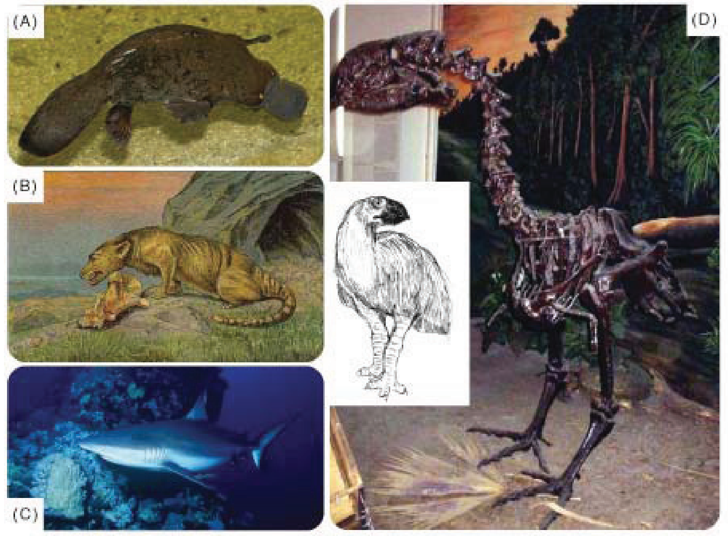

FIGURE 10.41
Mammals and birds quickly invaded ecological niches formerly occupied by the dinosaurs. Mammals included monotremes (A), marsupials, and hoofed placentals (B). Modern sharks (C) patrolled the seas. Birds included the giant flightless (D).

Lesson Summary

- During the 1800s, geologists, paleontologists and naturalists found several forms of physical evidence that confirmed that the earth is very old.
- Fossils of ancient sea life on dry land far from oceans supported the idea that the earth changed over time and that some dry land today was once covered by oceans.
- The many layers of rock represent the order in which rocks and fossils appeared.
- Indications that volcanic eruptions, earthquakes and erosion that happened long ago shaped much of the earth's surface.
- Radiometric dating allows scientists to measure the age of rocks by measuring the radioactivity of certain minerals in rocks.
- The oldest rock minerals found on Earth so far are zircon crystals that are at least 4.404 billion years old.
- Some of the oldest fossils of life forms on Earth are at least 3.5 billion year old fossils of blue green algae found in Australia.
- Scientists believe the early earth contained no oxygen gas, but did contain other gases, including nitrogen, carbon dioxide, carbon monoxide, water vapor, hydrogen sulfide and probably a few others.
- Geologists and other earth scientists use geologic time scales to describe when events occurred throughout the history of Earth.
- The geological time scale of Earth's past is organized according to events which took place during different periods on the time scale.
- Life on Earth began about 3.5 to 4 billion years ago.
- The first life forms were single cell organisms, prokaryotic organisms, similar to bacteria.
- The first multicellular organisms did not appear until about 610 million years ago in the oceans. Some of the first multicellular forms included sponges, brown algae, and slime molds.
- Plants and fungi appeared roughly 500 million years ago. They were soon followed by arthropods (insects and spiders).
- Amphibians evolved about 300 million years ago, followed by mammals around 200 million years ago and

birds around 100 million years ago.
- Extinction of species is common; in fact, it is estimated that 99% of the species that have lived on the earth no longer exist.
- Mass extinctions, such as the extinction of dinosaurs and many marine mammals, happened after major catastrophes such as volcanic eruptions and major earthquakes changed the environment.
- There have been at least five major massive extinctions have occurred in the past 540 million years.
- In each mass extinction, over 50% of animal species died.

Review Questions

1. How do scientists determine the age of a rock or fossil today?
2. How do we know the maximum possible age of the Earth?
3. How do we know the minimum possible age of the Earth?
4. How old is the Earth, based on current evidence?
5. Why is it difficult to determine how life started on Earth?
6. How long ago did life start on Earth?
7. When did mammals first appear on Earth?
8. What kinds of events are recorded on a geological time scale?

Vocabulary Students Need to Learn:

Fossils record

Adaptation

Mutation

Natural selection

Artificial selection

Geographical isolation

Reproductive isolation

Evolution

Trait

Species

Genetics

Vestigial structure

Homologous Structure

Embryology

Species

Phenotype

Genotype

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CHAPTER 11 Biological Classification Systems -Edited

Chapter Outline

11.1 Lesson 11.1: Classification Systems

Lesson Objectives

- Define taxonomy, and understand why scientists classify organisms.
- Describe Linnaean taxonomy and binomial nomenclature.
- Classify organisms into a hierarchy of groups based on similarities that reflect their evolutionary relationships.
- Classify organisms using a Dichotomous Key.
- Explain how evolutionary relationships are related to classification systems.

Introduction

Billions of years of evolution on Earth have resulted in a huge variety of different types of organisms. For more than two thousand years, humans have been trying to organize this great diversity of life. The classification system introduced by the Swedish botanist Carolus Linnaeus in the early 1700s has been the most widely used classification for almost 300 years.

Taxonomy

Scientific classification is a method by which biologists organize living things into groups. It is also called **taxonomy**. Groups of organisms in taxonomy are called **taxa** (singular, taxon). You may already be familiar with commonly used taxa, such as the kingdom and species. A **kingdom** (most inclusive) is the major grouping of organisms, such as plants or animals. A species (most exlcusive) includes only organisms of the same type, such as humans (*Homo sapiens*) or lions (*Panthera leo*). The modern biological definition of a **species** is a group of organisms that are similar enough to mate and produce fertile offspring together. In a classification system, kingdoms, species, and other taxa are typically arranged in a hierarchy of higher and lower levels.

This type of hierarchical classification can be demonstrated by classifying familiar objects. For example, a classification of cars is shown in **Figure** 11.111.1. The highest level of the classification system includes all cars. The next highest level groups cars on the basis of size. Then, within each of the size categories, cars are grouped according to first one and then another trait. Higher taxa (for example, compact cars) include many different cars. Lower taxa (for example, compact cars that are blue and have two doors and cloth seats) contain far fewer cars. The cars in lower taxa are also much more similar to one another.

Why do biologists classify organisms? The major reason is to make sense of the incredible **diversity of life** on Earth. Scientists have identified millions of different species of organisms. Among animals, the most diverse group of organisms is the insects. More than one million different species of insects have already been described. An estimated nine million insect species have yet to be identified. A tiny fraction of insect species is shown in the beetle collection in **Figure** 11.211.2.

As diverse as insects are, there may be even more species of bacteria, another major group of organisms. Clearly, there is a need to organize the tremendous diversity of life. Classification allows scientists to organize and better understand the basic similarities and differences among organisms. This knowledge is necessary to understand the present diversity and the past evolutionary history of life on Earth.

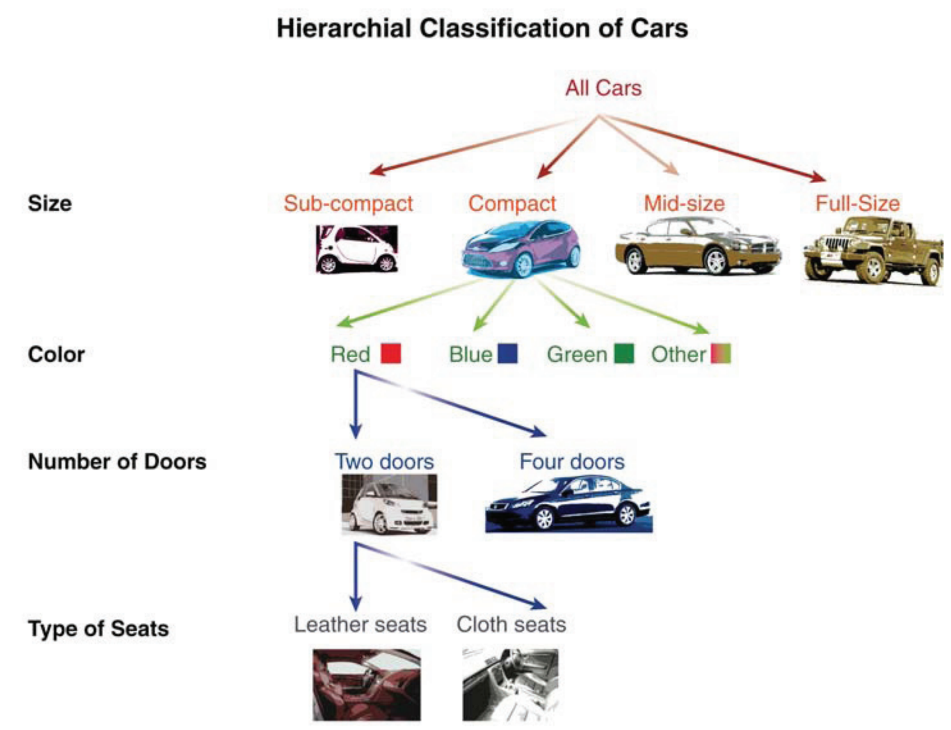

FIGURE 11.1
Cars can be classified, or grouped, on the basis of various traits. In this classification, the most inclusive groups are the size categories, such as all compact cars or all mid-size cars. The most exclusive groups in this classification share several additional traits, including color, number of doors, and type of seats. Note that just one group for each trait is further divided as an example.

Early Classification Systems

One of the first known systems for classifying organisms was developed by Aristotle. Aristotle was a Greek philosopher who lived more than 2,000 years ago. He created a classification system called the "Great Chain of Being" (See **Figure** 11.3). Aristotle arranged organisms in levels based on how complex, or "advanced," he believed them to be. There were a total of eleven different levels in his system. At the lower levels, he placed organisms that he believed were less complex, such as plants. At higher levels, he placed organisms that he believed were more complex. Aristotle considered humans to be the most complex organisms in the natural world. Therefore, he placed them near the top of his great chain, just below angels and other supernatural beings.

FIGURE 11.2
Only a few of the more than one million known species of insects are represented in this beetle collection. Beetles are a major subgroup of insects. They make up about 40 percent of all insect species and about 25 percent of all known species of organisms.

FIGURE 11.3
The Great Chain of Being was Aristotle

Aristotle also introduced two very important concepts that are still used in taxonomy today: genus and species. Aristotle used these two concepts in ways that are similar to, but not as precise as, their current meanings. He used the term *species* to refer to a particular type of organism. He thought each species was unique and unchanging. He used the term **genus** (plural, genera) to refer to a more general grouping of organisms that share certain traits. For example, he grouped together in the same genera animal species with similar reproductive structures.

As early naturalists learned more about the diversity of organisms, they developed different systems for classifying them. All these early classification systems, like Aristotle's, were based on obvious physical traits of form or function. For example, in one classification system, animals were grouped together on the basis of similarities in movement. In this system, bats and birds were grouped together as flying animals, and fishes and whales were grouped together as swimming animals.

Linnaean System of Classification

The most influential early classification system was developed by Carolus Linnaeus. In fact, all modern classification systems have their roots in Linnaeus' system. **Linnaeus** was a Swedish botanist who lived during the 1700s. He is known as the "father of taxonomy." Linnaeus tried to describe and classify the entire known natural world. In 1735, he published his classification system in a work called *Systema Naturae* ("System of Nature").

Linnaean taxonomy divides all of nature into three kingdoms: animal, vegetable (or plant), and mineral. (The mineral

kingdom does not include living organisms, so it is not discussed further here.) Both plant and animal kingdoms are subdivided into smaller and smaller categories of organisms. An updated version of Linnaean taxonomy is shown in **Figure** 11.411.4.

Linnaean Classification System (Revised)

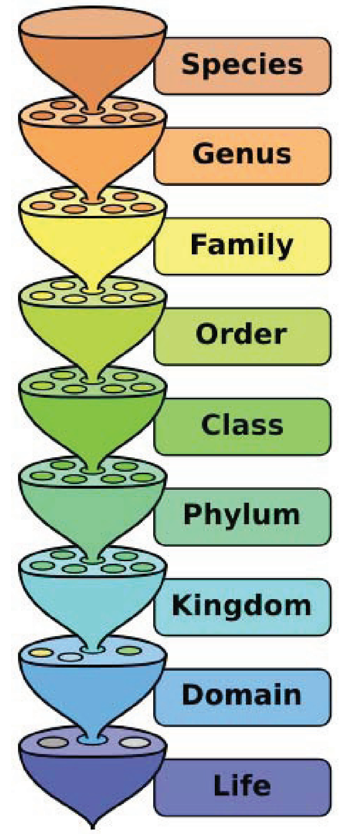

FIGURE 11.4
This is an updated version of Linnaeus

The classification in **Figure** 11.411.4 includes a few more taxa than Linnaeus identified. However, it follows the same general plan as Linnaeus' original taxonomy. The taxa are below:

- **Domain** This is the highest taxon. There are three domains: Bacteria, Archae, and Eukarya that includes all lifeforms.
- **Kingdom**—This is the next highest taxon in Linnaean taxonomy, representing major divisions of organisms. Kingdoms of organisms include the bacteria, protist, fungi, plant, and animal kingdoms.
- **Phylum** (plural, phyla)—This taxon is a division of a kingdom. Phyla in the animal kingdom include chordates (animals with an internal skeleton) and arthropods (animals with an external skeleton).
- **Class**—This taxon is a division of a phylum. Classes in the chordate phylum include fishes, amphibians, reptiles, birds, and mammals.
- **Order**—This taxon is a division of a class. Orders in the mammal class include rodents and primates.
- **Family**—This taxon is a division of an order. Families in the primate order include hominids (apes and humans) and hylobatids (gibbons).
- **Genus**—This taxon is a division of a family. Genera in the hominid family include *Homo* (humans) and *Pan* (chimpanzees).
- **Species**—This taxon is below the genus and the lowest taxon in Linnaeus' system. Species in the *Pan* genus include *Pan troglodytes* (common chimpanzees) and *Pan paniscus* (pygmy chimpanzees).

To remember the order of the taxa in Linnaean taxonomy, it may help to learn a mneumonic, a sentence to

help remember a list, in which the words begin with the same letters as the taxa: k, p, c, o, f, g, and s. One sentence you could use is: **King Philip came over for green sugar.** Can you think of others?

Table 11.111.1 shows the classification of the human species. The table also lists some of the physical traits that are the basis of the classification. For example, humans are members of the animal kingdom. Animals are organisms capable of independent movement. Within the animal kingdom, humans belong to the mammal class. Mammals are animals that have fur or hair and milk glands. At each lower taxon, additional physical traits further narrow the group to which humans belong. The final grouping, the species *sapiens* (as in *Homo sapiens*), includes only organisms that have all of the traits listed in the table.

TABLE 11.1: **Classification of the Human Species**

Taxon	Name	Traits[1]
Domain	Eukarya	All organisms that contain a nucleus in their cells (Eukaryotes)
Kingdom	Animal	Organisms capable of moving on their own.
Phylum	Chordate	Animals with a notochord (flexible rod that supports the body).
Class	Mammal	Chordates with fur or hair and milk glands.
Order	Primate	Mammals with collar bones, grasping hands with fingers.
Family	Hominid	Primates with three-dimensional vision, relatively flat face.
Genus	*Homo*	Hominids with upright posture, large brain.
Species	*sapiens*	Members of the genus *Homo* with a high forehead, thin skull bones.

[1] Only one or two traits per taxon are listed in the table as examples. Additional traits may be needed to properly classify species. (*Source :* http://en.wikipedia.org/wiki/Linnaean_taxonomy)

Although Linnaeus grouped organisms according to their physical similarities, he made no claims about relationships between similar species. Linnaeus lived a century before Charles Darwin, so the theory of evolution had not yet been developed. Darwin explained how evolution, or changes in species over time, can explain the diversity of organisms (see the *Evolutionary Theory* chapter). In contrast, Linnaeus (like Aristotle before him) thought of each species as an unchanging "ideal type." Individual organisms that differed from the species' ideal type were considered deviant and imperfect.

Binomial Nomenclature

The single greatest contribution that Linnaeus made to science is his method of naming species. This method, called **binomial nomenclature,** gives each species a unique, two-word name (also called a scientific or Latin name). Just like we have a first and last name, organisms have a distinguishable two word name as well. The two words in the name are the genus name and the species name. For example, the human species is uniquely identified by its genus and species names as *Homo sapiens.* No other species has this name.

Both words in a scientific name are Latin words or words that have been given Latin endings. The genus name is always written first and starts with an upper-case letter. The species name is always written second and starts with

a lower-case letter. Both names are written in italics. Why should we use Latin names instead of English names for animals?

As another example, consider the group of organisms called *Panthera.* This is a genus in the cat family. It consists of all large cats that are able to roar. Within the genus *Panthera,* there are four different species that differ from one another in several ways. One obvious way they differ is in the markings on their fur as shown in **Figure** 11.511.5, *Panthera leo* (lion species) has solid-colored fur, *Panthera tigris* (tiger species) has striped fur, and the other two *Panthera* species have fur with different types of spots. As this example shows, the genus name *Panthera* narrows a given cat's classification to big cats that roar. Adding the species name limits it to a single species of cat within this genus.

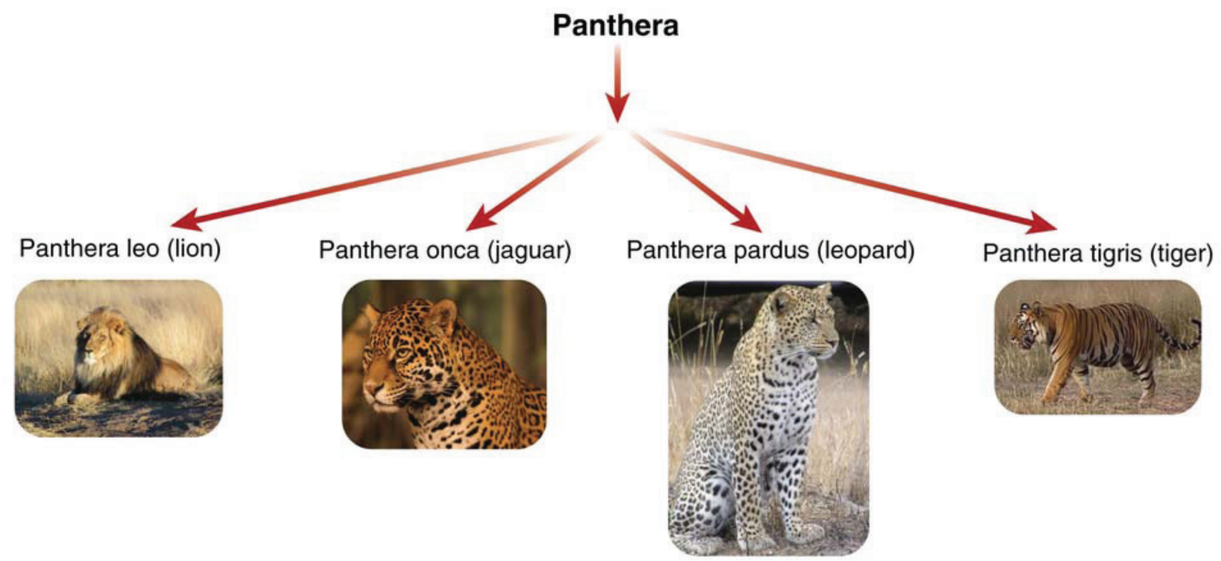

FIGURE 11.5

. All four species in the Panthera genus are similar, but each is a unique type of organism, clearly identified by its combined genus and species name.

Why is Linnaeus' method of naming organisms so important? Before Linnaeus introduced his method, naming practices were not standardized. Some names were used to refer to more than one species. Conversely, the same species often had more than one name. Do you know the difference between a mountain lion and a cougar? There is no difference, but in different parts of the world the same animal has many names. You could also call a cougar a puma or Florida panther. In addition, a name could be very long, consisting of a string of descriptive words. For example, at one time, common wild roses were named *Rosa sylvestris alba cum rubore folio glabro.* Names such as this were obviously cumbersome to use and hard to remember.

For all these reasons, there was seldom a simple, fixed name by which a species could always be identified. This led to a great deal of confusion and misunderstanding, especially as more and more species were discovered. Linnaeus changed all that by giving each species a unique and unchanging two-word name. Linnaeus's method of naming organisms was soon widely accepted and is still used today.

Changes in the Linnaean System

Linnaean taxonomy has been revised considerably since it was introduced in 1735. One reason revisions have been needed is that many new organisms have been discovered since Linnaeus' time. Another reason is that scientists started classifying organisms on the basis of evolutionary relationships rather than solely on the basis of similarities in physical traits.

Scientists have had to add several new taxa to the original Linnaean taxonomy in order to accommodate new knowledge of organisms and their evolutionary relationships. Examples of added taxa include the **subphylum**, **superfamily**, and **domain**.

- A subphylum is a division of a phylum that is higher than the class. An example of a subphylum is Vertebrates (animals with a backbone). It is a subphylum of the Chordate phylum (animals with a notochord).
- A superfamily is a taxon that groups together related families but is lower than the order. An example of a superfamily is Hominoids (apes). This superfamily consists of the Hominid family (gorillas, chimps, and humans) and the Hylobatid family (gibbons). **Figure** 11.6 shows species from both of these families of the Hominoid superfamily.
- A domain is a taxon higher than the kingdom. An example of a domain is Eukarya, which includes both plant and animal kingdoms.

FIGURE 11.6
The Hominoid superfamily includes the Hominid and Hylobatid families. Members of the Hominid family are chimpanzees (

Lesson Summary

- Taxonomy is the scientific classification of organisms. Scientists classify organisms in order to make sense of the tremendous diversity of life on Earth.
- Linnaean taxonomy groups organisms in a hierarchy of taxa, based on similarities in physical traits. Linnaeus' binomial nomenclature gives each species a unique two-word name.

Review Questions

1. Define taxonomy.
2. What contributions did Carolus Linnaeus make to taxonomy?
3. List the order of taxa in Linnaean taxonomy, from most to least inclusive.
4. What is binomial nomenclature?

5. Create a hierarchical taxonomy to classify writing implements, such as pens and pencils. Use a diagram to show your taxonomy.
6. Assume that a new organism has been discovered. It has a notochord, fur, forward-facing eyes, and grasping hands with fingers. In which taxa should the new organism be placed? Justify your answer.
7. Explain why biologists need to classify organisms.
8. Why was Linnaeus' naming system such an important contribution to biology?

Points to Consider

Linnaeus grouped together organisms on the basis of similarities in physical traits.

- Can you think of other similarities that could be used to group organisms?
- What other types of traits might related organisms share?
- What about similarities in molecules, such as DNA, among related organisms?

11.2 Lesson 11.2: Phylogenetic Classification

Lesson Objectives

- Understand the concept of phylogenetic classification.
- Outline how cladistics generates cladograms and identifies clades.
- Compare phylogenetic and Linnaean classification systems.
- Explain how nucleic acid base sequences are used in phylogenetic classification.

Introduction

In the century after Linnaeus published his system of classification, ideas about classifying organisms began to change. In 1859, Darwin published his major work on evolution, *On the Origin of Species by Natural Selection.* After that, there was more and more interest in classifying organisms, incorporating the evolutionary history, including the genetic relationships, of the organisms.

Phylogeny

The evolutionary history of a group of genetically related organisms is called a **phylogeny**. It includes ancestor species and descendant species. A phylogeny is usually represented by a tree diagram called a **phylogenetic tree**. An early example of a phylogenetic tree is Darwin's "Tree of Life" (see **Figure** 11.711.7). In this diagram, Darwin was trying to show how he thought evolution had occurred. The tree shows how species evolved through time, from the bottom of the tree to the top. As species evolved, they formed new branches on the tree of life. Some of these species eventually branched into additional descendant species. Others died out, or went extinct, without leaving any descendants.

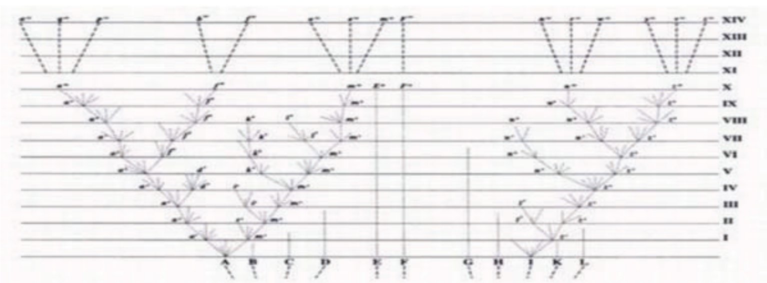

FIGURE 11.7
. This branching diagram represents the evolutionary histories of different species. It is the only diagram that originally appeared in Darwin

Modern biologists still use phylogenetic trees to represent evolutionary histories. A simple phylogenetic tree is shown in **Figure** 11.811.8. The tips of the branches represent genetically related species. The branching points represent common ancestors. A **common ancestor** is the last ancestor species that two descendant species shared before they took different evolutionary paths. In the tree in **Figure** 11.811.8, species 1 and 2 shared a more recent common ancestor with each other than with species 3. Therefore, species 1 and 2 are more closely related to one another than to species 3.

Ancestor species are like your own ancestors. Your most recent common ancestor with any siblings you may have is a shared parent. Your most recent common ancestor with a first cousin is a shared grandparent. Your most recent

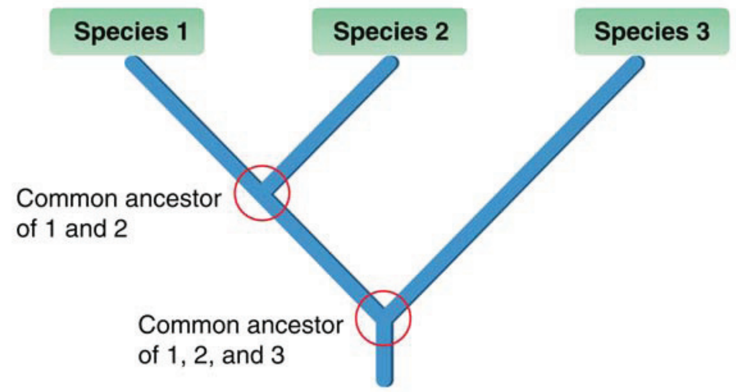

FIGURE 11.8
. This phylogenetic tree shows how hypothetical species 1, 2, and 3 are related to one another through common ancestors.

common ancestor with a second cousin is a shared great-grandparent. In general, the more distant the relationship between you and relatives in your own generation, the farther in the past you shared a common ancestor. The same holds true for related species. The more distant the relationship between two related species, the farther back in time they shared a common ancestor.

The most common method of incorporating information into phylogenetic trees is called **cladistics**. Cladistics depicts hypotheses about how organisms are related, based on traits of ancestor and descendent species. Cladistics was developed in the 1950s by a scientist named Willi Hennig. Over the next several decades, it became very popular, and is still widely used today.

The term *cladistics* comes from the word *clade*. A **clade** is a group of organisms that includes an ancestor species and all of its descendants. A diagram showing evolutionary relationships within one or more clades is called a **cladogram**. A clade is a relative concept. How you define a clade depends on which species you are interested in classifying. Small clades can includes as few as two species and their common ancestor. Traits inherited from a common ancestor are called **ancestral traits**. Traits that evolved since two groups shared a common ancestor are called **derived traits.** The larger clades can include many more species and their common ancestors.

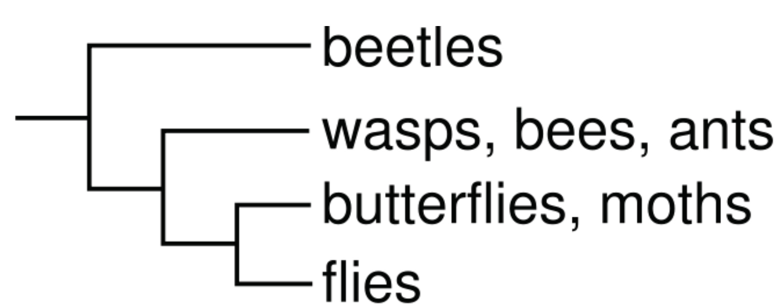

FIGURE 11.9
Cladogram of Insect Phylogeny. Based on this cladogram, flies shared a more recent common ancestor with butterflies and moths than either group shared with other insects. What other evolutionary relationships does the cladogram reveal?

A derived trait is not necessarily an entirely new trait. More often it is a modified form of an ancestral trait. For example, birds evolved feathers from the scales that were already present in their reptile ancestor. Similarly, mammals evolved fur from the scales of their reptile ancestor.

Phylogenetic Classification

A cladogram shows how species may be related by descent from a common ancestor. A classification of organisms on the basis of such relationships is called a **phylogenetic classification**. A phylogenetic classification involves

placing organisms in a clade with their common ancestor. Consider the cladogram in **Figure** 11.9. It groups birds in the same clade as reptiles, because a variety of evidence suggests that birds evolved from a reptile ancestor. The cladogram places mammals in a separate clade, because evidence suggests that mammals evolved from a different ancestor.

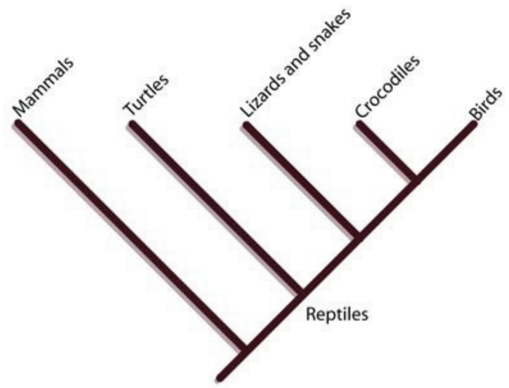

FIGURE 11.10

. This cladogram represents the evolutionary history of reptiles, birds, and mammals. The reptile clade includes birds. Mammals are in a separate clade.

Figure 11.1111.10 shows the phylogenetic classification of reptiles, birds, and mammals based on the cladogram in **Figure** 11.10. Birds are grouped with reptiles in one clade, called the Sauropsids. Mammals and their reptile-like ancestor are grouped in a separate clade, called the Synapsids. Compare this phylogenetic classification with the Linnaean classification, also shown in **Figure** 11.1111.11. In the Linnaean classification, reptiles, birds, and mammals are all placed in separate classes based on differences in physical traits. This classification artificially separates both birds and mammals from their reptilian ancestors. It also illustrates the difficulty of showing evolutionary relationships with Linnaean taxonomy.

Phylogenetic and Linnaean Classifications of Reptiles, Birds, and Mammals

Both phylogenetic and Linnaean classification systems have advantages and drawbacks (see the point by point comparison in the two lists, below). As an overall approach, most biologists think that phylogenetic classification is preferable to Linnaean classification. This is because it is based on evolutionary relationships and not just similarities in physical traits that may or may not have evolutionary significance. However, both approaches have a place in the classification of organisms. Linnaean binomial names are still needed to identify species, because phylogenetics does not include a method for naming species. In addition, many higher taxa in the Linnaean system, such as birds and mammals, remain useful in phylogenetic classifications. This is because they are also clades.

Phylogenetic Classification

1. Treats all levels of a cladogram as equivalent.
2. Places no limit on the number of levels in a ladogram.
3. Primary goal is to show the process of evolution.
4. It is limited to organisms that are related by ancestry.
5. Does not include a method for naming species.

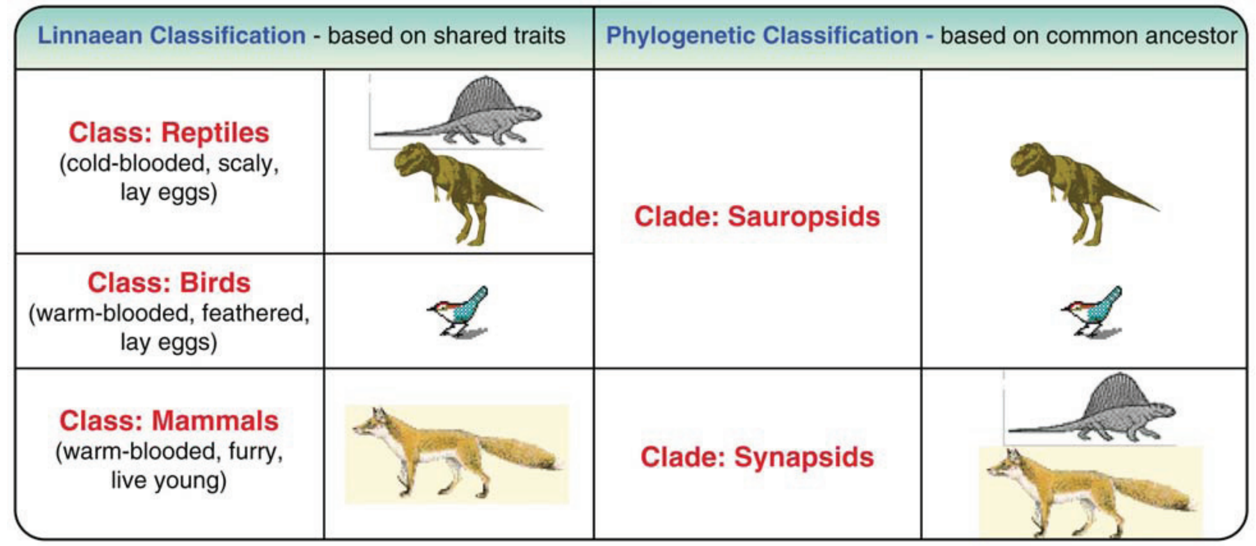

FIGURE 11.11

The cladistic classification on the right assumes that mammals and birds evolved from different reptile ancestors. Mammals are placed in one clade, and birds are placed in another clade (with modern reptiles). Compare this classification with the Linnaean classification on the left. Why are birds and reptiles placed in separate classes in the Linnean taxonomy

Linnaean Classification

1. Treats each taxa uniquely and has a special name or each (e.g., genus, species).
2. Has fixed numbers and types of taxa.
3. Primary goal is to group species based on similarities in physical traits.
4. Can include any organisms without regard to ancestry.
5. Has a method for giving unique names to species.

Dichotomous Keys

A 'key' in Biology is a modeling method used for categorizing species using logical choices. A **Dichotomous key** is a key where the sequence and structure of identification steps is fixed by the author of the key. At each point in the decision process, multiple alternatives are offered, each leading to a result or a further choice. The alternatives are commonly called "leads", the set of leads at a given point a "couplet". At each step (or lead), the user must answer a question about one or more features (*characters*) of the entity to be identified. For example, a step in a botanical key may ask about the color of flowers, or the disposition of the leaves along the stems. A key for insect identification may ask about the number of bristles on the rear leg.

If the entire key consists of exactly two choices at each branching point, the key is called **dichotomous**. The majority of keys are dichotomous.

Dichotomous Key – Family: Candius

1a. Candy is chewy.......................2
1b. Candy is hard........................7

2a. Candy is wrapped....................3
2b. Candy is not wrapped................Ursa gummius

3a. Candy is rounded....................4
3b. Candy is not rounded................5

4a. Wrapper is all white..................Saltus taffinia
4b. Wrapper is not all white...............5

5a. Wrapper is brown and white........Tutus rollus
5b. Wrapper is not brown and white....6

6a. Wrapper is silver.....................Chocolatus cyssan
6b. Wrapper varies in color.............Stellaria explodus

7a. Candy is spherical (ball-shaped)....8
7b. Candy is not spherical..............9

8a. Candy is wrapped....................11
8b. Candy is unwrapped.................Mandibulus crackus

9a. Wrapper is transparent...............10
9b. Wrapper tells the flavor............Joyous rancheria

10a. Wrapper is clear...................Mintus stripus
10b. Wrapper is yellow.................Ranunculus scotchus

11a. Candy is on a stick.................Moronus moronus
11b. Candy is not on a stick............Spherus combustus

FIGURE 11.12
Here is an example of following the steps to identify various candies. Can you identify the scientific names of the candies?

FIGURE 11.13
Use these candies and the Dichotomous Key to find the candy's

Evidence for Evolutionary Relationships

Traditionally, evidence for evolutionary relationships included similarities in physical traits of form or function. For example, in Linnaean taxonomy, homeothermy (warm-bloodedness) is one of the traits used to separate both birds and mammals from other animals. However, this trait is not suitable for showing evolutionary relationships between birds and mammals. This is because birds and mammals did not inherit the trait of homeothermy from a common ancestor. Both groups independently evolved the trait. The presence of homeothermy in both birds and mammals is an example of convergent evolution. In general, convergent evolution may make two groups seem to be more closely related than they really are. Using such traits for phylogenetic analysis can lead to misleading phylogenetic

classifications.

Similarities among DNA nucleic acid base sequences provide some of the most direct evidence of evolutionary relationships. DNA directly control genetic traits and copies of nucleic acids are actually passed from parents to offspring. Therefore, similarities in these traits are likely to reflect shared ancestry. By the 1960s, scientists had found ways to sequence the bases in nucleic acids. This coincided with the growing popularity of cladistics. In cladistic analysis, similar nucleic acid base sequences are assumed to indicate descent from a common ancestor. The more similar the sequences, the more recently two groups are assumed to have shared a common ancestor.

Many DNA base sequence comparisons have confirmed genetic relationships that were assumed on the basis of similarities in physical traits. For example, 96 percent of the DNA in humans and chimpanzees is the same. This agrees, in general, with the Linnaean classification of chimpanzees as close human relatives.

Most biologists interested in taxonomy now use DNA nucleic acid sequences (molecular homologies) or other related molecular data to classify organisms. However, using nucleic acid base sequences for phylogenetic analysis is not without its drawbacks. Two of the drawbacks are:

- Data on DNA can rarely be obtained for extinct species. This is true even for species represented by fossils. Fossil DNA and RNA generally are not sufficient in quantity or quality to be useful for such analyses.

Lesson Summary

- Phylogeny is the evolutionary history of a group of genetically related organisms. It is usually represented by a diagram called a phylogenetic tree.
- Cladistics is the most widely used method of generating phylogenetic trees. It is based on evolutionary ancestry and generates trees called cladograms. Cladistics also identifies clades, which are groups of organisms that include an ancestor species and its descendants.
- Classifying organisms on the basis of descent from a common ancestor is called phylogenetic classification. Phylogenetic classification may or may not agree with Linnaean taxonomy, which is based on similarities in physical traits regardless of ancestry.
- The most direct evidence for evolutionary relationships is similarity in base sequences of the nucleic acids DNA and RNA. The more similar the base sequences of two species, the more closely related the species are assumed to be.

Review Questions

1. What is a phylogeny?
2. Define cladistics.
3. What does phylogenetic classification involve?
4. Why are nucleic acid base sequences directly related to evolution?
5. Identify an ancestral trait and a derived trait in mammals. Explain your answer.
6. Explain why a cladogram represents only one hypothesis about how evolution occurred.
7. Compare the advantages of Linnaean and phylogenetic classification systems.
8. Using the "Candy" dichotomous key list the common names of each candy next to their scientific name.
9. What evidence is there that birds and reptiles are related?

11.3 Lesson 11.3: Modern Classification Systems

Lesson Objectives

- Identify the four new kingdoms that were added to the original Linnaean taxonomy.
- Describe the three domains of the three-domain system of classification.
- Explain why the three-domain system may need revision in the future.

Introduction

Linnaeus established two kingdoms of organisms in his classification system: Plantae (the plant kingdom) and Animalia (the animal kingdom). Since then, scientists have repeatedly revised the Linnaean system. They have added several new kingdoms and other taxa. These changes were necessary as scientists learned more about life on Earth.

New Kingdoms

Between 1866 and 1977, a total of four new kingdoms were added to the original plant and animal kingdoms identified by Linnaeus. The new kingdoms include Protista (protists), Fungi, Monera (eubacteria), and Archaea (archaebacteria). **Table** 11.211.2identifies the scientists who introduced the kingdoms and the dates the kingdoms were introduced. The table starts with the two-kingdom system introduced by Linnaeus in 1735.

TABLE 11.2: Kingdoms in the Classification of Organisms

Number of Kingdoms	Two	Three	Four	Five	Six
Scientist	Linnaeus	Haeckel	Copeland	Whittaker	Woese
Date	1735	1866	1956	1969	1977
Names of Kingdoms	Animalia Plantae	Protista Animalia Plantae	Monera Protista Animalia Plantae	Monera Fungi Protista Animalia Plantae	Archaea Bacteria Fungi Protista Animalia Plantae

(*Source:* http://en.wikipedia.org/wiki/Kingdom_%28biology%29, *License:* GNU Free Documentation)

The Protist Kingdom

When Linnaeus created his taxonomy, microorganisms were almost unknown. As scientists began studying single-celled organisms under the microscope, they generally classified them as either plants and or animals. For example, bacteria are single-celled organisms, some of which make their own food. They were classified as plants, which also make their own food. Protozoa are single-celled organisms that can move on their own. They were classified as animals, which are organisms that have independent movement.

As more single-celled organisms were identified, many didn't seem to fit in either the plant or the animal kingdom. As a result, scientists could not agree on how to classify them. To address this problem, in 1866, biologist Ernst

Haeckel created a third kingdom for all single-celled organisms. He called this kingdom Protista. **Figure** 11.1411.4 shows drawings that Haeckel made of several different types of **protists** as they looked under a microscope. The drawings show some of the diversity of microorganisms.

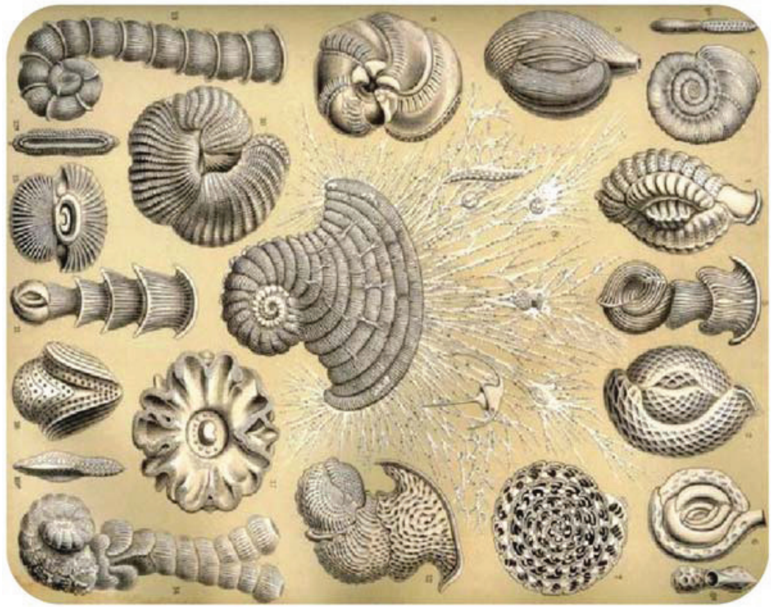

FIGURE 11.14
. Biologist Ernst Haeckel made these drawings of various types of single-celled organisms as viewed under a microscope. Based on his extensive knowledge of the diversity of microorganisms, Haeckel introduced a new kingdom just for single-celled life forms, called the protist kingdom. This was the first major change in the original Linnaean taxonomy.

The Bacteria Kingdom

Haeckel's protist kingdom represented all known single-celled organisms, including both bacteria and protozoa. In the early 1900s, scientists discovered that bacterial cells are very different not only from plant and animal cells but also from the cells of protists, such as protozoa. **Figure** 11.1511.15 shows a bacterial cell, a protozoan cell, and an animal cell. When you compare the three cells, what differences do you see? The major difference is that, unlike the protozoan and animal cells, the bacterial cell does not contain a nucleus surrounded by a nuclear membrane. Instead, its DNA is found in the cytoplasm of the cell. Organelles in the bacterial cell also lack surrounding membranes.

In the 1920s, microbiologist Edouard Chatton gave bacteria the name prokaryotes. He defined **prokaryote** as an organism whose cells lack nuclei. He gave the name eukaryotes to all other organisms. He defined **eukaryote** as an organism whose cells have nuclei (see the *Cell Structure and Function* chapter). Chatton proposed placing prokaryotes and eukaryotes in a new taxon above the kingdom, called the superkingdom. However, this idea did not catch on, and most biologists continued to place bacteria in the protist kingdom.

Over the next several decades, scientists learned more about the tremendous number and diversity of bacteria. They started to see a need for a separate bacteria kingdom. By 1956, biologist Herbert Copeland proposed placing bacteria in a new kingdom called Monera. With the addition of the **Monera** kingdom, Linnaean taxonomy became a four-kingdom system (See **Table** 11.211.2).

Bacteria are the most numerous organisms on Earth. In a single gram of soil, there are typically 40 million bacterial cells. The human body also contains 10 times as many bacterial cells as human cells. Most of these bacteria are on the skin or in the digestive tract.

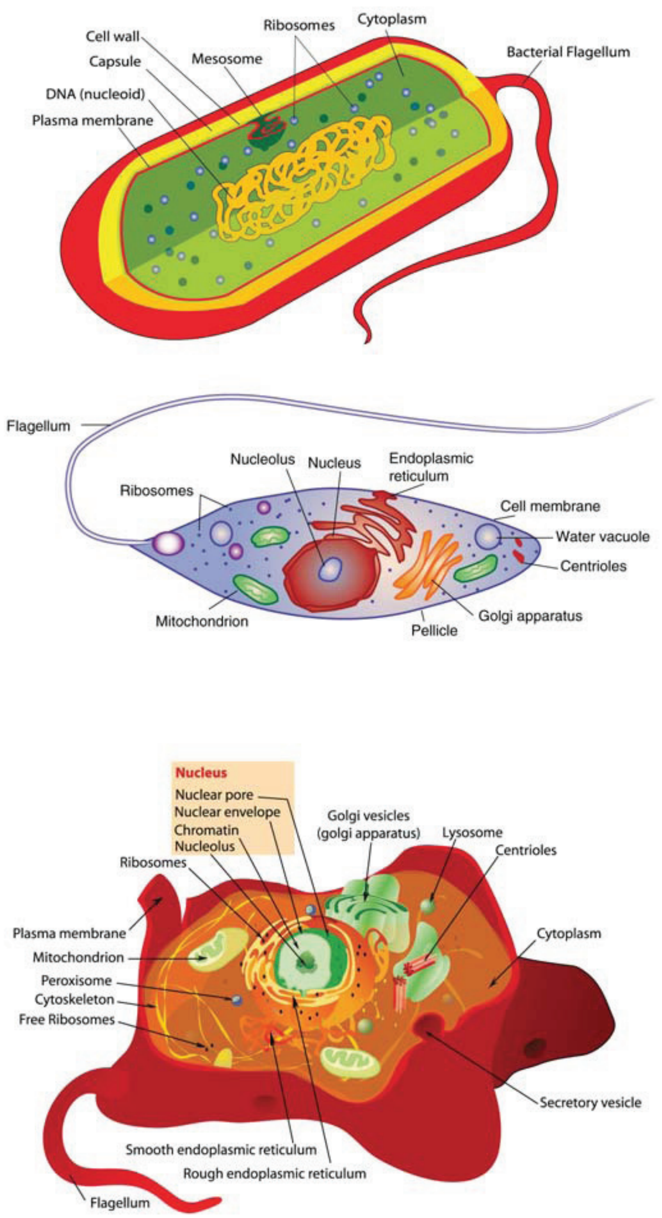

FIGURE 11.15

. Prokaryote and eukaryote cells differ significantly in their structure. Unlike prokaryote cells (upper figure), eukaryote cells (middle figure, protist cell; lower figure, animal cell) have a nucleus, which is separated by membranes from the cytoplasm of the cell. Their organelles also have membranes. Herbert Copeland thought that these and other differences were significant enough to place prokaryote and eukaryote organisms in different superkingdoms.

The Fungi Kingdom

In the late 1960s, ecologist Robert Whittaker proposed adding a fifth kingdom to Linnaean taxonomy to represent fungi. **Fungi** are eukaryote organisms such as mushrooms and molds. Up until then, fungi had been classified in the plant kingdom. Whittaker separated fungi from plants on the basis of differences in metabolism. Plants make their own food in the process of photosynthesis, whereas fungi obtain nutrients by breaking down dead organisms. Separating fungi from plants resulted in five kingdoms, which are illustrated in **Figure** 11.16. The five-kingdom system soon became widely accepted.

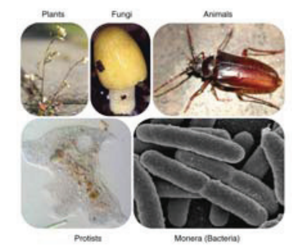

FIGURE 11.16

This five-kingdom system of classification was proposed by ecologist Robert Whittaker in the late 1960s. Whittaker added the Fungi kingdom to the earlier four-kingdom classification system.

Two Bacterial Kingdoms

By the 1970s, scientists had started to classify organisms in ways that reflected evolutionary relationships. They had also started using nucleic acid base sequences to identify these relationships (see Lesson 14.2). Nucleic acid sequence data are especially useful for studying bacteria. These organisms are so small that they have few physical traits.

Studies have bacterial nucleic acid sequences have yielded some surprising results. For example, in their research on ribosomal RNA base sequences, microbiologist Carl Woese and his colleagues discovered that bacteria actually include two very different groups of organisms. They called the two groups Eubacteria and Archaebacteria. Examples of organisms from each group are shown in **Figure** 11.17. Although the two types of organisms are similar in appearance, their ribosomal RNA sequences are very different. In 1977, Woese and his colleagues suggested that the original bacteria kingdom should be divided into two new kingdoms, called Eubacteria and Archaebacteria. This resulted in a six-kingdom taxonomy that has been widely accepted for many years.

FIGURE 11.17

Left, Eubacteria (now called Bacteria), Right, Archaebacteria (now called Archaea). Appearances can be deceiving! These two microorganisms are very different from one another, despite their outward similarities. Both organisms used to be classified in the bacteria kingdom. Woese suggested placing them in different kingdoms, called the eubacteria and archaebacteria kingdoms.

Domains

Woese wasn't completely happy with the six-kingdom system. It didn't show that all four eukaryote kingdoms are more closely related to each other than to the two bacteria kingdoms. It also didn't show that the two bacteria kingdoms are as different from each other as they are from the eukaryote kingdoms. To show these similarities and differences, Woese introduced a new taxon called the **domain**. He defined domain as a taxon higher than the kingdom.

The Three-Domain System

In 1990, Woese and his colleagues proposed a new classification system containing three domains: Bacteria, Archaea, and Eukarya. As shown in **Figure**11.18, the **Bacteria** domain was formerly the Eubacteria kingdom, and the **Archaea** domain was formerly the Archaebacteria kingdom. The **Eukarya** domain includes all four eukaryote kingdoms: plants, animals, protists, and fungi. The three-domain system emphasizes the similarities

among eukaryotes and the differences among eukaryotes, bacteria, and archaea. By using domains, Woese was able to show these relationships without replacing the popular six-kingdom system.

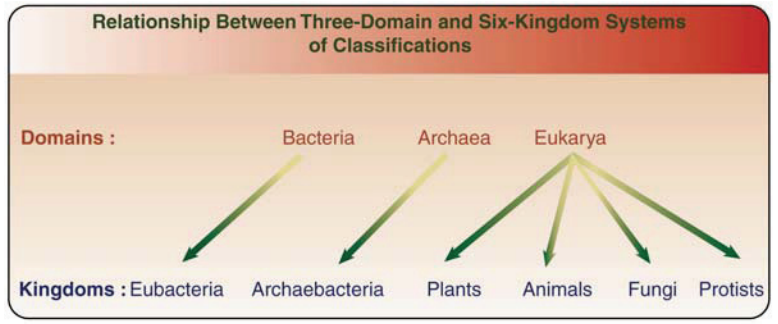

FIGURE 11.18
This diagram shows how the three-domain system of classification is related to the six-kingdom system. Both Eubacteria and Archaebacteria kingdoms are raised to the level of domains (Bacteria and Archaea domains, respectively) in the three-domain system. The other four kingdoms make up the third domain (Eukarya domain).

Archaea were first found in extreme environments. For example, they were found in the hot water geysers in Yellowstone National park. Archaea have since been found in all of Earth's habitats. They are now known to be present everywhere in high numbers. They may contribute as much as 20 percent to Earth's total biomass.

Woese's three-domain system was quickly adopted by many other biologists. There were some critics, however, who argued that the system put too much emphasis on the uniqueness of Archaea. Later studies confirmed how different Archaea are from other organisms. For example, organisms belonging to Archaea were found to differ from both Eukarya and Bacteria in the composition of their cell membranes and the system they use for DNA replication. These differences convinced most critics that the three-domain system was justified. After its introduction in 1990, the three-domain system became increasingly popular. Within a decade of its introduction, it had largely replaced earlier classifications.

How Are the Three Domains Related?

Comparing ribosomal RNA base sequences, Woese and his colleagues also showed that organisms belonging to Eukarya are more similar to Archaea than they are to Bacteria. **Figure** 11.1911.19 is a phylogenetic tree based on their analysis. This tree places Archaea and Eukarya in the same clade (see Lesson 2). It represents the hypothesis that Archaea and Eukarya shared a more recent common ancestor with each other than with Bacteria.

The results of a study published in 2007 seem to conflict with this hypothesis. Comparing DNA base sequences, the 2007 study suggested that the domain Archaea may be older than either Bacteria or Eukarya. That would make Archaea the most ancient group of organisms on Earth. It is not yet known, which, if either, hypothesis is correct. Scientists need to learn more about Archaea and their relationships with other organisms to resolve these questions.

Lesson Summary

- By 1977, four new kingdoms had been added to the plant and animal kingdoms of the original Linnaean taxonomy: Protista, Fungi, Eubacteria, and Archaebacteria.
- In 1990, the three-domain system was introduced and is now the most widely used classification system. The three domains are Bacteria, Archaea, and Eukarya.
- As knowledge of organisms increases in the future, the three-domain system may need revision. For example, new domains may need to be added.

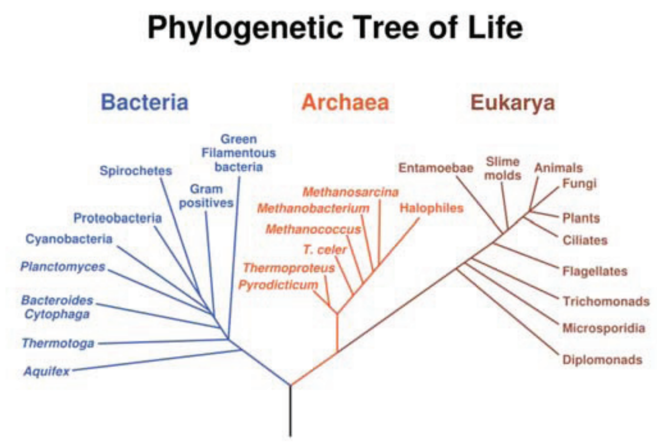

FIGURE 11.19
This phylogenetic tree is based on comparisons of ribosomal RNA base sequences among living organisms. The tree divides all organisms into three domains: Bacteria, Archaea, and Eukarya. Humans and other animals belong to the Eukarya domain. From this tree, organisms that make up the domain Eukarya appear to have shared a more recent common ancestor with Archaea than Bacteria.

Review Questions

1. Name four new kingdoms that were added to the original Linnaean taxonomy.
2. How do prokaryotes and eukaryotes differ?
3. Why were fungi placed in a separate kingdom from plants?
4. What is a domain?
5. Describe the relationship between the original bacteria kingdom called monera and the domain called bacteria.
6. Explain in which domain you would classify an organism that consists of a single cell with a nucleus.
7. Compare and contrast bacteria, Archaea, and Eukarya.
8. What problem with the six-kingdom classification system was addressed by the three-domain classification system? How did it address the problem?

Vocabulary Students Need to Learn:

Binomial nomenclature

Species

Taxonomy

Eukaryote

Prokaryote

Cladogram

Dichotomous key

Phylogeny

Points to Consider

Robert Whittaker separated the fungi from the plant kingdom on the basis of their different ways of obtaining energy. You might expect Whittaker to focus on this type of difference because he was an ecologist.

- What do you think ecology is?
- What do you think ecologists study?

- In addition to ways of obtaining energy, what traits of organisms do you think ecologists are likely to be most interested in?

11.4 References

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CHAPTER 12 Animal and Plant Anatomy Physiology - Edited

Chapter Outline

12.1 Organization of the Human Plant Body

Lesson Objectives

- Describe the levels of organization of the human body.
- Outline the role of a specialized cell.
- Identify the properties that make body cells and stem cells different from each other.
- Describe the structure and function of organs
- Identify the four tissue types found in the human body and the three types of tissue found in plants.
- Summarize how tissues and organs relate to each other.
- Name two body systems that work together for a common purpose.
- Identify the process by which body systems are kept within certain limits.
- Describe the relationship between structure and function of organ systems in plants and animals.

Introduction

How are living organisms similar to a well-tuned machine?

Many people have compared the bodies of organism to machines. Think about some common machines, such as drills and washing machines. Each machine consists of many parts, and each part does a specific job, yet all the parts work together to perform an overall function. The bodies of living organisms are like machines in all these ways. In fact, they may be the most fantastic machines on Earth.

As a preview of one of the machines, the human machine, the Emmy award-winning video, *Inside The Living Body,* at this link is highly recommended:http://www.youtube.com/watch?v=chqwSh4ii84&feature=related.

Levels of Organization

The human machine is organized at different levels, starting with the cell and ending with the entire organism (see **Figure** below). At each higher level of organization, there is a greater degree of complexity.

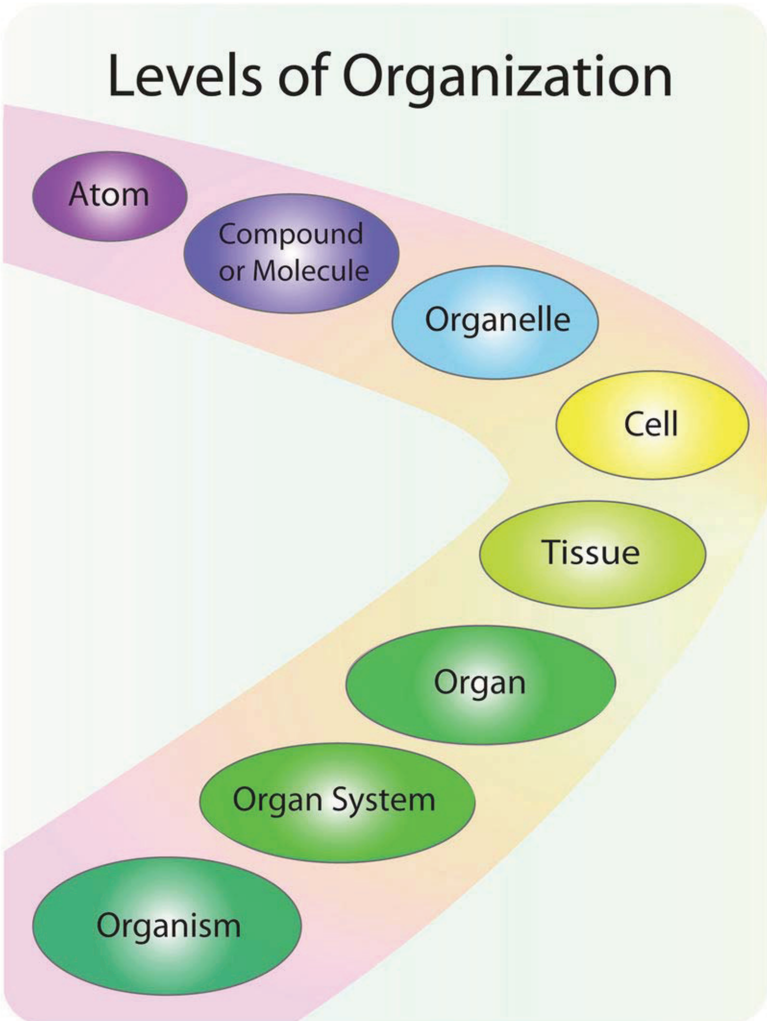


FIGURE 12.1

CELLS

The most basic parts of living machines are cells—an amazing 100 trillion of them by the time the average person reaches adulthood! **Cells** are the basic units of structure and function in all living things. Each cell carries out basic life processes that allow the body to survive. Many animal cells are specialized in form and function, as shown in **Figure** below. In most multicellular organisms, not all cells are alike. For example, the cells that make up your skin are different from cells that make up your liver, your blood, or your eyes. Yet, all these specialized cells develop from one single fertilized egg which means all of your cells have the same DNA. But liver, blood, and eye cells are very different from each other in form and function. While these cells are specialized for a specific job, there are other cells in the body that remain unspecialized. These cells multiply continuously to replace the millions of different body cells that die and need to be replaced every day. Each type of cell plays a specific role. For example, nerve cells have long projections that help them carry electrical messages to other cells. Muscle cells have many mitochondria that provide the energy they need to move the body.

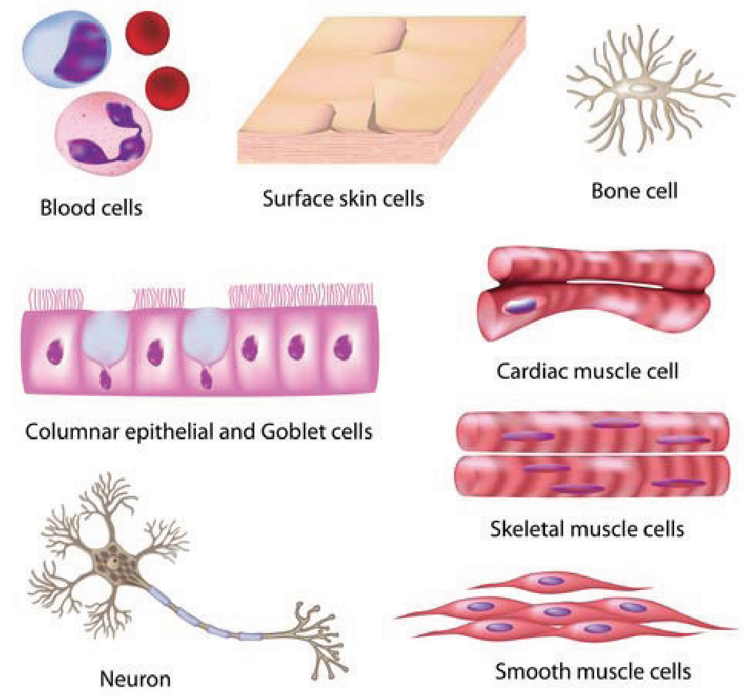


FIGURE 12.2

You can watch a video about some of the specialized cells of the human body and how they function at this link: http://www.youtube.com/watch?v=I8uXewS9dJU&feature=related

Plants are also multicellular organisms where not all the cells are alike. For example, the cells that make up a stem are different from cells that make up a root, or a leaf. Yet, all these specialized cells develop for one embryo so they all have the same DNA. Each specialized cell has a specific function. For example, nerve cells transmit electrical messages around the body, and white blood cells patrol the body and attack invading bacteria, vascular plant cells transport materials throughout the plant, guard cells which regulate the release of water and oxygen out of the plants **stomata**. Other cells include specialized cells in the kidney (such as kidney glomerulus parietal cell), brain cells (such as astrocytes), stomach cells (such as parietal cells), muscle cells (such as red and white skeletal muscle fibers), and in plants Sclerenchyma cells are hard and tough cells with a function in mechanical support, Parenchyma cells are living cells that have diverse functions ranging from storage and support to photosynthesis and phloem loading.

Differentiation

Every cell in the body originated from a single fertilized egg, which is called a **zygote**. The zygote divides many times to produce an embryo. These embryonic cells differentiate into many different cell types which in time give rise to all the cells types present in the body of all humans (and other mammals), from a new-born baby to an elderly adult. **Differentiation** is the process by which an unspecialized cell (such as a fertilized egg cell), divides many times to produce specialized cells that work together and make up the body. During differentiation, certain genes are turned on, or become activated, while other genes are switched off, or inactivated. This process is regulated by the cell. A differentiated cell will develop specific structures and perform certain functions.

A cell that is able to differentiate into all cell types within a body is called **totipotent**. They have "total potential" to differentiate into any cell type. In mammals, only the zygote and early embryonic cells are totipotent. A cell that is able to differentiate into many cell types, but not all, is called **pluripotent**. Such cells have "plural potential," (but not "total potential") to differentiate into most but not all cell types.

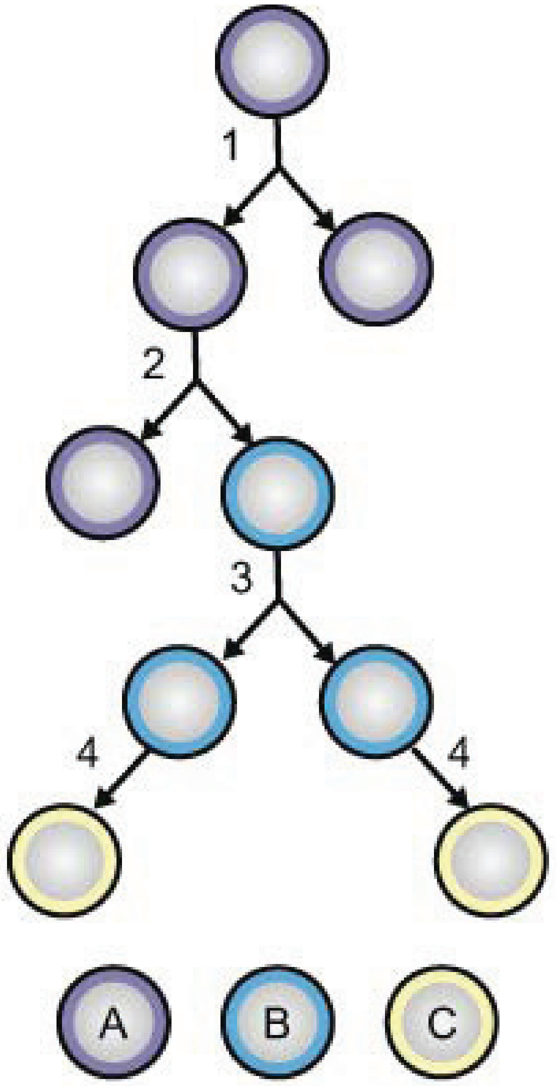


FIGURE 12.3

A–Embryonic stem cells (purple)
B–adult stem cell (blue)
C–differentiated cell (yellow)
1–embryonic stem cell division to make more stem cells
2–totipotent embryonic stem cells can produce pluripotent adult stem cells
3–adult stem cells divide, and eventually differentiate into specialized cells. (4)

Stem Cells

An unspecialized cell that can divide many times and give rise to different, specialized cells is called a **stem cell**, as shown in **Figure** above. Zygotes and embryonic cells are both types of stem cells. The stem cells found in embryos can divide indefinitely, can specialize into any cell type and are called **embryonic stem cells**. Embryonic stem cells are totipotent. Undifferentiated cells that are found within the body and that divide to replace dying cells and

damaged tissues are called **adult stem cells**. Adult stem cells can divide indefinitely, and generate all the cell types of the organ from which they originate. They can potentially re-grow the entire organ from just a few cells. A third type of stem cell is found in blood from the umbilical cord of a new-born baby, and the placenta. These "cord blood stem cells" are considered to be adult stem cells because they cannot generate all body cell types, just different types of blood cells. Therefore, adult stem cells and cord blood stem cells are pluripotent.

Stem Cells in Medicine

Stem cells are of great interest to researchers because of their ability to divide indefinitely, and to differentiate into many cell types. Stem cells have many existing or potential therapeutic applications. Such therapies include treatments for cancer, blood disorders, brain or spinal cord injuries, and blindness.

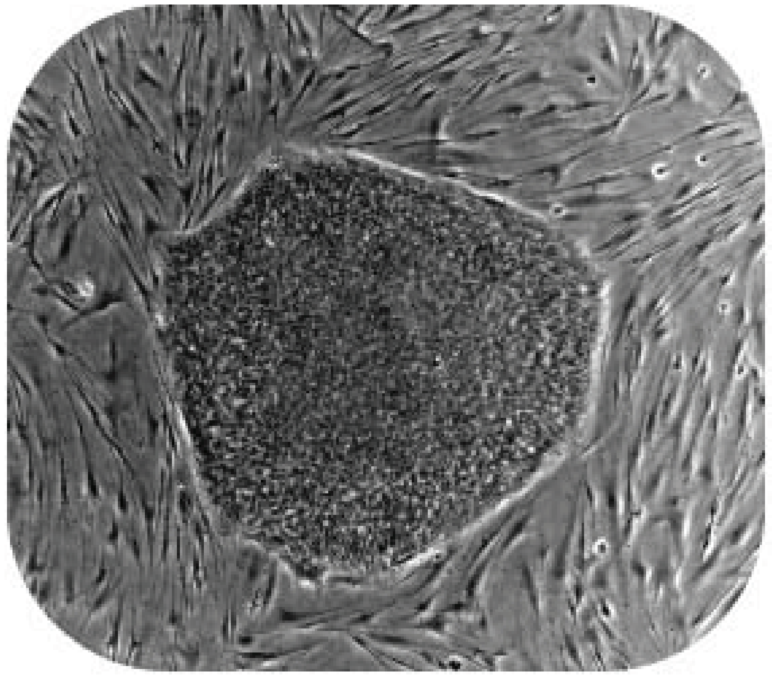


FIGURE 12.4

Embryonic stem cells, as shown in **Figure** above, are taken from eggs that were fertilized in the laboratory and donated to research. They may have the greatest potential because they are totipotent, and thus have the most potential medical applications. However, embryonic stem cells harvested from a donated embryo differ from a potential patient's tissue type. Therefore, just as in organ transplantation, there is a risk of a patient's body rejecting transplanted embryonic stem cells. Some individuals and groups have objections to the harvesting of embryonic stem cells, because harvesting the stem cells involves the destruction of the embryo. Some researchers are looking into methods to extract embryonic stem cells without destroying the actual embryo. Other researchers have claimed success in harvesting embryonic stem cells from the embryonic fluid that surrounds a growing fetus.

Adult stem cells, including cord blood stem cells, have already been used to treat diseases of the blood such as sickle-cell anemia and certain types of cancer. Unlike embryonic stem cells, the use of adult stem cells in research and therapy is not controversial because the production of adult stem cells does not require the destruction of an embryo. Adult stem cells can be isolated from a tissue sample, such as bone marrow, from a person. Scientists have recently discovered more sources of adult stem cells in the body. Adult stem cells have been found in body fat, the inside lining of the nose, and in the brain. Some researchers are investigating ways to revert adult stem cells back to a totipotent stage.

Organisms are made up of trillions of cells that all work together for the maintenance of the entire organism. While cells, tissues, and organs may perform very different functions, all the cells in the body are similar in their

metabolic needs. Maintaining a constant internal environment by providing the cells with what they need to survive (oxygen, nutrients, and removal of waste) is necessary for the well-being of individual cells and of the entire body. The many processes by which the body controls its internal environment are collectively called homeostasis. The complementary activity of major body systems maintains homeostasis.

Tissues

After the cell, the tissue is the next level of organization in the human body. A **tissue** is a group of connected cells that have a similar function within an organism. The simplest living multicellular organisms, sponges and mosses, are made of many specialized types of cells that work together for a common goal.

Complex organisms such as jellyfish, coral, and sea anemones have a tissue level of organization. For example, jellyfish have tissues that have separate protective, digestive, and sensory functions. There are four basic types of tissue in the body of all animals, and three basic tissue types in plants. These make up all the organs, structures and other contents of the organism. **Figure** below shows an example of each tissue type.

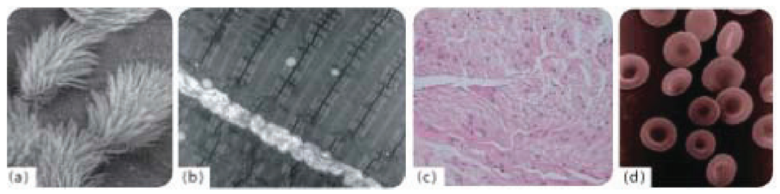


FIGURE 12.5

(a) Scanning electron micrograph (SEM) image of lung trachea epithelial tissue, (b) Transmission electron micrograph (TEM) image of skeletal muscle tissue, (c) Light microscope image of neurons of nervous tissue, (d) red blood cells, a connective tissue.

The four basic types of animal tissue are:

- **Epithelial tissue** is made up of layers of tightly packed cells that line the surfaces of the body for protection, secretion, and absorption. Examples of epithelial tissue include the skin, the lining of the mouth and nose, and the lining of the digestive system.
- **Muscle tissue** is made up of cells contain contractile filaments that move past each other and change the size of the cell. There are three types of muscle tissue: smooth muscle which is found in the inner linings of organs; skeletal muscle, which is attached to bone and moves the body; and cardiac muscle which is found only in the heart.
- **Nervous tissue** is made up of the nerve cells (neurons) that together form the nervous system, including the brain and spinal cord.
- **Connective tissue** is made up of many different types of cells that are all involved in structure and support of the body. Bone, blood, fat, and cartilage are all connective tissues. Connective tissue can be densely packed together, as bone cells are, or loosely packed, as adipose tissue (fat cells) are.

The three basic types of plant tissue are:(displayed in the image below)

1. **Epidermis**- the exchange of matter between the plant and the environment.
   (a) the epidermis on aboveground organs (leaves and stems) is involved with gas exchange
   (b) the epidermis on belowground organs (roots) is involved with water and ion uptake
2. **Vascular tissues**- the transport of water and dissolved substances inside the plant
   (a) the xylem carries water and dissolved ions from the roots to stems and leaves

   (b) the phloem carries dissolved sugars from the leaves to all other parts of the plant
3. **Ground tissues**- metabolism, storage, and support activities
   (a) the ground tissue of the leaf (called mesophyll) uses the energy in sunlight to synthesize sugars in a process known as photosynthesis
   (b) the ground tissue of the stem (called pith and cortex) develops support cells to hold the young plant upright
   (c) the ground tissue of the root (also called cortex) often stores energy- rich carbohydrates

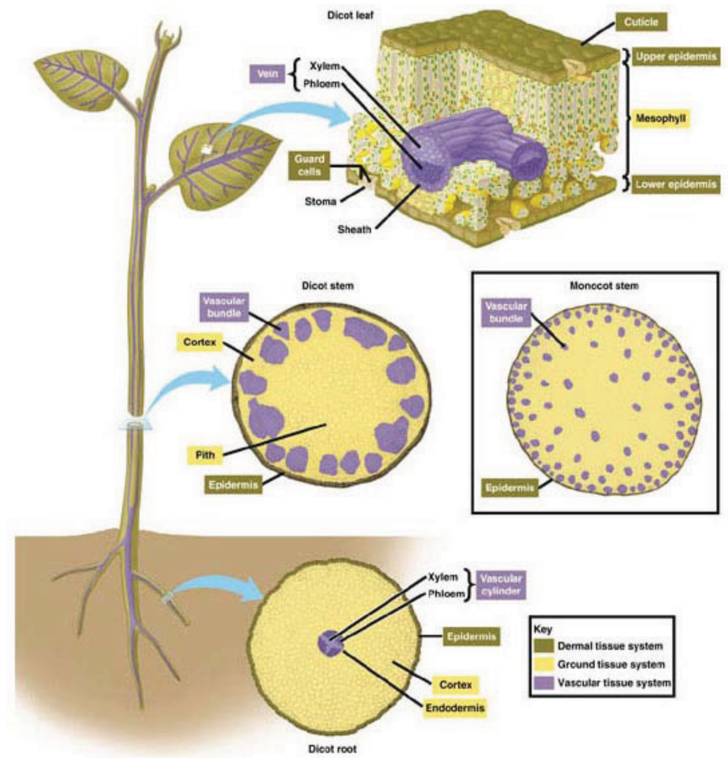


FIGURE 12.6

The three tissue types of plants.

Plants have two groups of tissue: Meristematic tissues which consist of actively dividing cells this are found in regions such as the tips of stems or roots and lead to increases in length and thickness of the plant these cells are spherical oval polygonal and rectangular and have thin cells walls. Permanent tissue takes on a specific role and loses the ability to divide.

Organs and Organ Systems

After tissues, organs are the next level of organization in the body. An **organ** is a structure made of two or more tissues that work together for a common purpose. Skin, the largest organ in the body, is shown in **Figure** below. Organs can be as primitive as the brain of a flatworm (a group of nerve cells), as large as the stem of a sequoia (up to 90 meters in height (300 feet)), or as complex as a human liver. The human body has many different organs, such as the heart, the kidneys, the pancreas, and the skin. Plants have only three major organs; the leaves, the stems, and the roots. The flower is also an organ of plants, but is not found on all types of plants. Two or all of the tissue types can be found in an organ. Organs inside the body are called internal organs. The internal organs collectively are often called viscera.

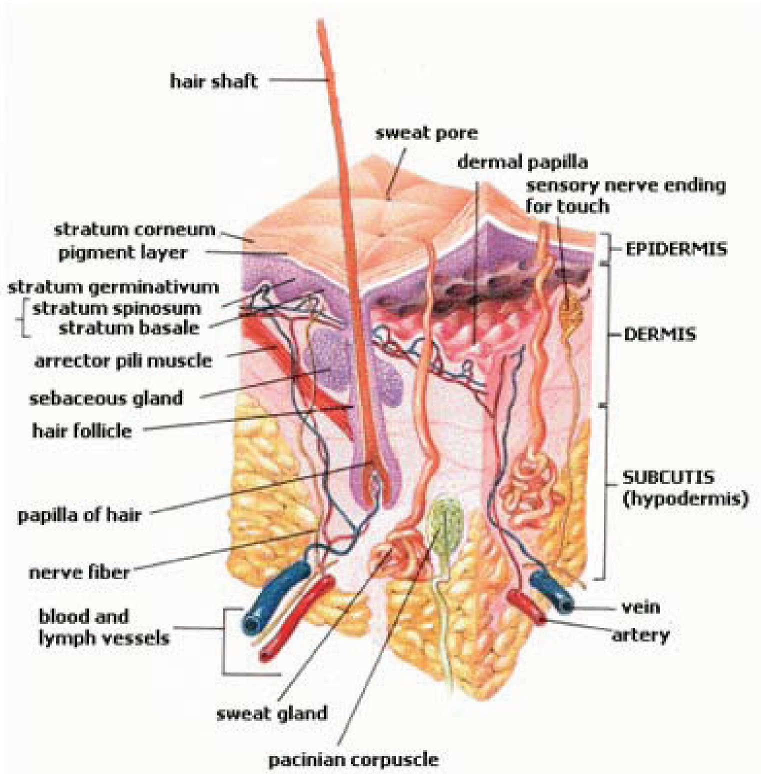


FIGURE 12.7
Your skin is the largest organ in your body. In this cross section image of skin, the four different tissue types (epithelial, connective, nervous, and muscle tissues) can be seen working together.

The most complex organisms have organ systems, the level of organization after organs. An **organ system** is a group of organs that act together to carry out complex interrelated functions, with each organ focusing on a part of the task. An example of an organ system is the human digestive system, which contains mostly hollow organs, in which the mouth and esophagus ingests food, the stomach crushes and liquefies it, the pancreas and gall bladder make and release digestive enzymes, and the intestines absorb nutrients into the blood. An organ can be part of more than one organ system. For example the ovaries produce hormones which make them a part of the endocrine system. The ovaries, which are small solid organs, also make eggs which makes them part of the reproductive system. One of the most important functions of organ systems is to provide cells with oxygen and nutrients and removes toxic waste products such as carbon dioxide. A number of organ systems, including the cardiovascular and respiratory systems, work together to do this.

You can watch overviews of the human organ systems and their functions at the links below.

- http://www.youtube.com/watch?v=po8D290YF9o&feature=related
- http://www.youtube.com/watch?v=SSqwRkDLyH4&feature=related
- http://www.youtube.com/watch?v=KidJ-2H0nyY&feature=player_embedded#!

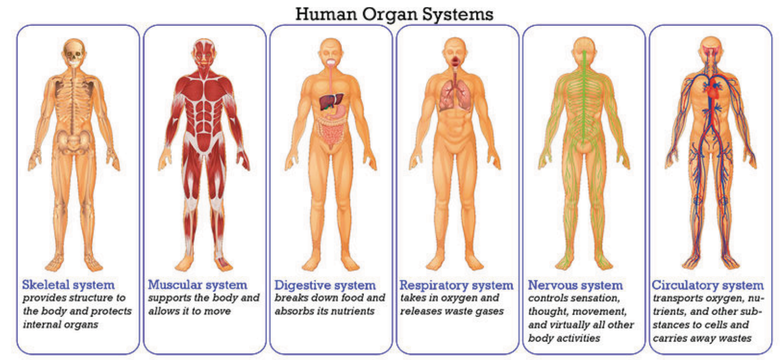


FIGURE 12.8

The different organ systems of the body are shown in **Table** 12.1. Sometimes the cardiovascular system and the lymphatic system are grouped together into one single system called the circulatory system.

TABLE 12.1: Major Organ Systems of the Human Body

Organ System	Function	Organs, Tissues, and Structures Involved
Cardiovascular	Transporting oxygen, nutrients and other substances to the body cells, and wastes, carbon dioxide, and other substances away from cells; it can also help stabilize body temperature and pH	Heart, blood, blood vessels
Lymphatic	Defense against infection and disease, transfer of lymph between tissues and the blood stream	Lymph, lymph nodes, lymph vessels
Digestive	Processing of foods and absorption of nutrients, minerals, vitamins, and water	Salivary glands, esophagus, stomach, liver, gallbladder, pancreas, small intestine, large intestine
Endocrine	Communication within the body with hormones; directing long-term change over other organ systems to maintain homeostasis	Among many, the pituitary gland, pineal gland, thyroid, parathyroid gland, adrenal glands, testes, and ovaries
Integumentary	Protection from injury and fluid loss; physical defense against infection by microorganisms; temperature control	Skin, hair, and nails
Muscular	Movement, support, heat production	Skeletal, cardiac, and smooth muscles, tendons
Nervous	Collecting, transferring and processing information; directing short-term change over other organ systems in order to maintain homeostasis	Brain, spinal cord, nerves, and sense organs (eyes, ears, tongue, skin, nose)
Reproductive	Production of gametes (sex cells) and sex hormones; production of offspring	Fallopian tubes, uterus, vagina, ovaries, mammary glands, testes, vas deferens, seminal vesicles, prostate, and penis

TABLE 12.1: (continued)

Organ System	Function	Organs, Tissues, and Structures Involved
Respiratory	Delivery of air to sites where gas exchange can occur between the blood and cells (around body) or blood and air (lungs)	Mouth, nose, pharynx, larynx, trachea, bronchi, lungs, and diaphragm
Skeletal	Support and protection of soft tissues of body; movement at joints; production of blood cells; mineral storage	Bones, cartilage, ligaments
Urinary	Removal of excess water, salts, and waste products from blood and body; control of pH	Kidneys, ureters, urinary bladder, and urethra
Immune	Defending against microbial pathogens (disease-causing agents) and other diseases	Leukocytes, tonsils, adenoids, thymus, and spleen

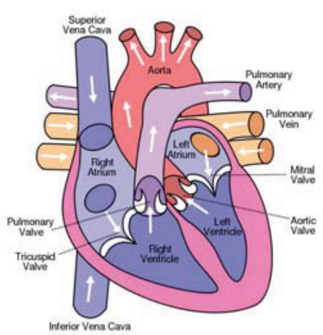


FIGURE 12.9

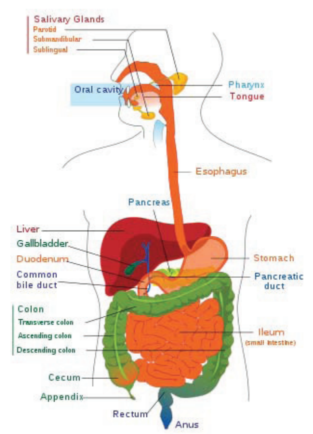


FIGURE 12.10

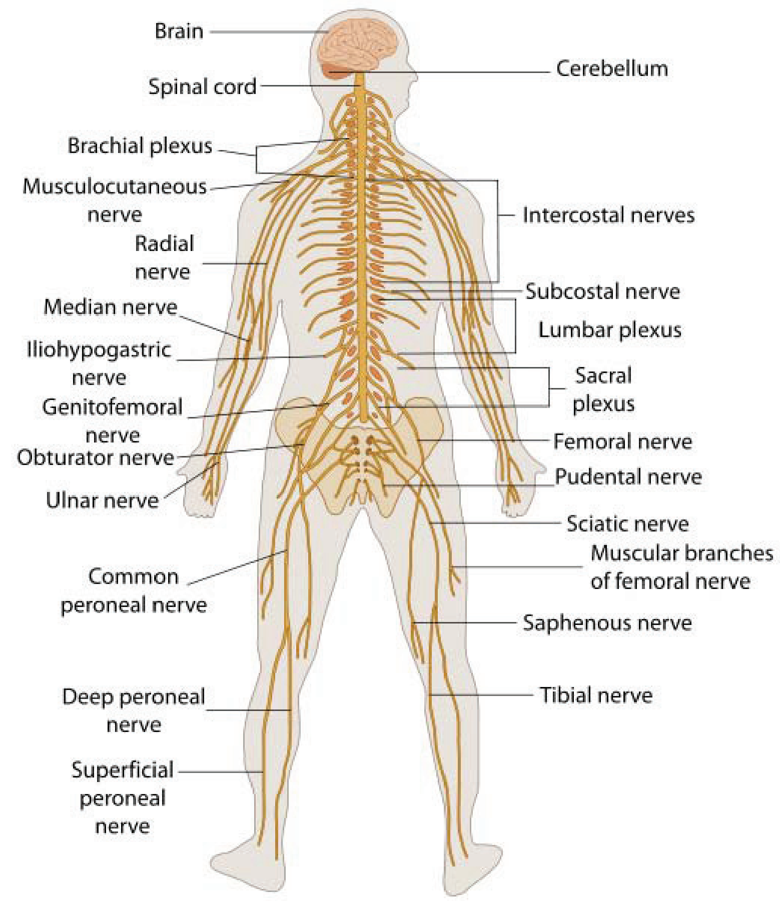


FIGURE 12.11

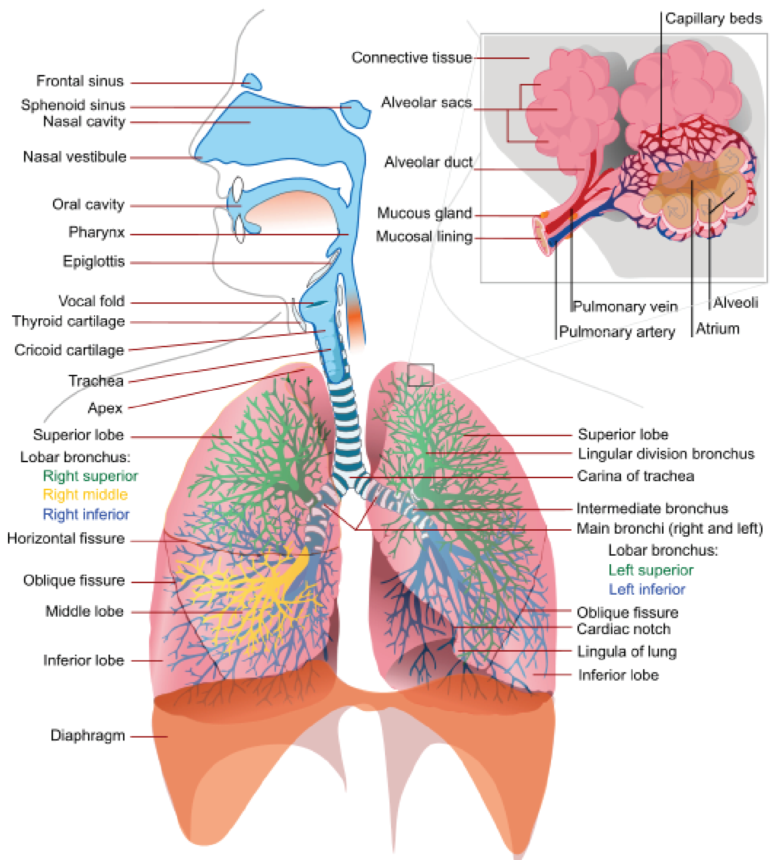


FIGURE 12.12

Plants have three major organs: leaves, stems, and roots

TABLE 12.2: Plant organs and their function

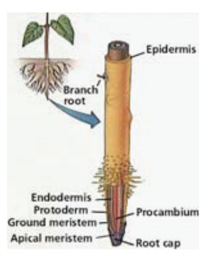
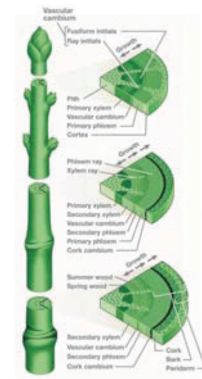
Organ	Function	Picture
Roots	Anchorage absorption of water and dissolved minerals Storage (surplus sugars transported from leaves Conduction	
Stems	Conduction of water and sugars throughout plant Support leaves and Fruits	
Leaves	Perform Photosynthesis Regulate water loss of the plant Abscission (leaf fall)	

TABLE 12.2: (continued)

TABLE 12.3:

Flowers	Contain reproductive organs Attract pollinators Produce fruit	

A plant has two organ systems: 1) the **shoot** system, and 2) the **root** system. The shoot system is above ground and includes the organs such as leaves, buds, stems, flowers (if the plant has any), and fruits (if the plant has any). The root system includes those parts of the plant below ground, such as the roots, tubers, and rhizomes.

Homeostasis

Homeostasis refers to stability, balance, or equilibrium within a cell or the body. It is an organism's ability to keep a constant internal environment. Homeostasis is an important characteristic of living things. Keeping a stable internal environment requires constant adjustments as conditions change inside and outside the cell. The adjusting of systems within a cell is called homeostatic regulation. Because the internal and external environments of a cell are constantly changing, adjustments must be made continuously to stay at or near the set point (the normal level or range). Homeostasis can be thought of as a dynamic equilibrium rather than a constant, unchanging state. All the structures of living organisms assist in maintaining homeostasis. For example, in animals carbon dioxide is an acid. If an animal stops breathing, the carbon dioxide builds up causing the pH to lower. When the pH gets too low the animals will passout. Breathing in oxygen and out carbon dioxide keeps the blood pH in the normal range. In plant cells there is a large vacuole to store water. To maintain homeostasis the vacuole absorbs or releases water.

Lesson Summary

- Not all cells are alike in a multicellular organism, but all of the cells in a multicellular organism have the same DNA.
- Each specialized cell has a specific function in the body. Specialized cells group together to carry out a specific function.
- Every cell in the body originated from a single zygote. The unspecialized zygote differentiates to produce specialized cells that work together and make up the body.
- A cell that is able to differentiate into all cell types within a body is totipotent. Embryonic stem cells are totipotent.
- A cell that is able to differentiate into many cell types, but not all types, is pluripotent. Adult stem cells and cord blood stem cells are pluripotent.
- A tissue is a group of connected cells that have a similar function within an organism. There are four basic types of tissue in the body of all animals: connective, muscle, nervous, and epithelial.
- An organ is a structure made of two or more different types of tissue that work together for a common purpose.
- An organ system is a group of organs that act together to carry out complex related functions, with each organ focusing on a part of the task.

Resources

- http://www.hippocampus.org/Biology → Biology for AP* → Search: **Animal Form and Function: Overview,** The Structure of Animal Tissue, Organs and Organ Systems
- **Organs Game at http://www.bbc.co.uk/science/humanbody/body/index_interactivebody.shtml.**

Review Questions

1. Starting with the smallest level of organization list all the levels of organization.
2. Give three examples of specialized cells.
3. Contrast specialized cells and stem cells.
4. List the four tissue types that are found in the human body, and the three tissue types found in plants and then give an example of each type.
5. Which **type** of tissue covers the surface of the body?
6. List the organs of a plant and where the organs would be found.
7. These cells form the lining of the trachea. Identify the cells and the type of tissue of which the ciliated cells in **Figure**below are a part.

FIGURE 12.13

8. Summarize the relationship between tissues and organs.
9. Outline the importance of homeostasis to an organism.
10. Identify an organ that is part of two body systems. Then explain how it helps each body system.

11. A classmate says that the lymphatic system should not be an organ system in its own right, and is a part of the cardiovascular system. Do you agree or disagree with your classmate? Explain your answer by using your knowledge of organ systems.
12. What are the functions of the Skeletal system?
13. What are the functions of the Digestive system?
14. What are the functions of the Respiratory system?
15. What are the functions of the Nervous system?
16. What are the functions of the Circulatory system?
17. What organs of a plant serve a similar function as the organs found in the cardiovascular system?
18. You are a surgeon at the local hospital and have been called on to perform an emergency surgery. The patient had his arm cut off at the elbow and his friends could only find his hand. You are called upon to reattach the hand to the arm, but because it was such an emergency there are only plant tissues that can be used to connect the hand. Explain what tissues of a plant could be used to reattach a hand to an elbow and the function they would serve on a human.

Points to Consider

- The smallest unit capable of carrying out life processes in your body is a single cell. Cells organize into tissues, which organize into organs. Groups of organs work together as organ systems. Consider how the last meal you consumed is interacting with each level of organization in your body.
- Think about the advantages and disadvantages of having a body composed of many small cells as opposed to a single large cell.
- Homeostasis is an organism's ability to maintain a stable internal environment. Homeostasis is an important characteristic of living things. Keeping a stable internal environment requires constant adjustments as conditions change inside and outside the cell.

Vocabulary Students Need to Learn:

Cell

Organ

Tissue

Organ system

Stomata

Stem cell

Organism

Structure

Function

12.2 References

1. CK-12 Foundation. Bio35a-1-n1. CCSA

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